MIT Technology Review

VOL. 118 NO. 5 SEPTEMBER/OCTOBER 2015 US $6.99/CAN $7.99

Review p. 100

Is Elon Musk a Great Man?

Review p. 88

Big Bet on Solar

Feature p. 70

Computers with Common Sense

35 INNOVATORS UNDER 35

0 74470 01308 2 10

Let's begin.
October 5 - 8, 2015

solve.mit.edu

A WATERSHED FOR WATERSHEDS.

Half of the Everglades has already disappeared. Now the remaining half of this fragile ecosystem is at risk from pollutants in stormwater runoff.

The problem has been decades in the making. But the millions of Florida residents, visitors and native animals relying on this watershed don't have decades to wait for a solution. So the South Florida Water Management District designed innovative stormwater treatment wetlands and Citi found a way to finance the project in weeks rather than years. Now, clean water from those wetlands is replenishing the Everglades and an incomparable global landmark is on the mend.

For over 200 years, Citi's job has been to believe in people and help make their ideas a reality.

citi.com/progress

citi®
The World's Citi SM

From the Editor

Seven over 70

Every year we celebrate 35 innovators under the age of 35. We choose to write about the young simply because we want to introduce you to the most promising new technologists, researchers, and entrepreneurs.

But older people are, of course, just as capable of new thinking as the young. Below are seven innovators over the age of 70, still working.

1. Bob Kahn, who is 76, invented (with Vint Cerf) the Transmission Control Protocol (TCP) and the Internet Protocol (IP), the communication protocols that relay data around the Net, and was responsible for the systems design of the Arpanet, the first packet-switched network. Today he is the chairman and CEO of the Corporation for National Research Initiatives (CNRI), an organization he founded that funds and develops network-based technologies. His most recent research has focused on the development of a "digital object architecture," which enables various information systems and resources to work together.

2. Sidney Yip, born in 1936, is a professor emeritus of nuclear science and engineering at MIT. After notionally retiring in 2009—having taught for 44 years and published more than 300 papers and the *Handbook of Materials Modeling* (2005), the standard reference book in the field—he continues to do important research. For instance, he suggested (with MIT senior research scientist Roland Pellenq) a new recipe for concrete that increases its strength while reducing the carbon emissions associated with producing cement.

3. Judith Jarvis Thomson, 85, another of MIT's professors emeriti, is a philosopher best known for the elaboration of thought experiments called "trolley problems," which test our moral intuitions. In the most famous trolley problem of all, Thomson asks her readers to imagine pushing a fat man onto a track in order to stop a runaway trolley from running over five people. She remains keenly interested in questions of rights and normativity (whether, ethically, one *ought* to do or refrain from doing something). Trolley problems are useful in thinking how autonomous vehicles and military robots could be programmed to behave in ways consistent with most people's moral intuitions.

4. The great chemist **John Polanyi**, who was awarded the Nobel Prize in 1986 for his contributions toward understanding the dynamics of elementary chemical processes, is still busy at age 86. His work at the University of Toronto uses scanning tunneling microscopes to study chemical reactions that might help us build devices at very small scales. Polanyi's father, Michael, the Hungarian chemist, philosopher, and economist, defended the liberty of scientific thought; the son, too, is concerned with public affairs, and he often speaks or writes about nuclear weapons and social justice.

5. Paul Greengard, born in 1925 and a 2000 Nobel laureate in medicine, still works on average six days a week, from 9 A.M. to 10 P.M., at Rockefeller University, where he researches what causes brain disorders like Alzheimer's disease and schizophrenia. One major area of research in Greengard's lab is the search for the cellular and molecular basis of depression; his researchers recently described a protein that plays a central role in the regulation of moods.

6. Helen Murray Free, 92, developed a series of self-testing kits for diabetes while working at Miles Laboratories in the second half of the last century. The tests transformed the way people with diabetes monitor their disease, helping make it into a manageable condition. Since retiring in 1982, she has devoted herself to promoting science education, particularly for young women and minorities.

7. Rudolph A. Marcus, who is 92, is a Caltech chemist who was awarded the 1992 Nobel Prize "for his contributions to the theory of electron transfer reactions in chemical systems." The Marcus theory, named for him, describes the rates at which an electron can move or jump from one chemical species to another. Today the Marcus Group at Caltech researches a wide variety of chemical phenomena, including ozone gas formation and semiconductor quantum dots.

But write to me at jason.pontin@technologyreview.com, and tell me your favorite counterexamples to the prevailing youth chauvinism.

GUIDO VITTI

HOW DOES A CANCELED FLIGHT ARRIVE SIX HOURS EARLY?

IT'S SIMPLE.
THE ANSWER IS SAP HANA.

What if you could react to unforeseen events with unprecedented agility? SAP HANA® is helping one major airline crunch petabytes of data and a multitude of variables to cut the time it takes them to respond to unanticipated events—from six hours to less than a minute. What could your enterprise do? For more, go to **sap.com/simple**

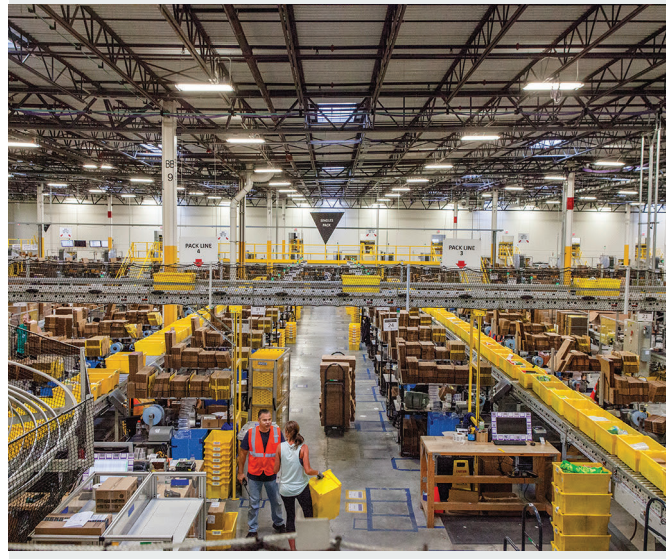
SAP®

Run Simple

Contents

Front

September/October 2015



Inside the Amazon fulfillment machine, p. 62

Back

BUSINESS REPORT

REVIEWS

54 YEARS AGO

ON THE COVER:

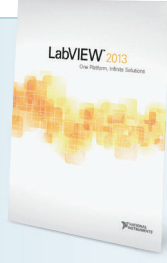
Illustration by Bendik Kaltenborn

PHOTOGRAPH BY LAUREN LANCASTER

Smarter Embedded Designs,
Faster Deployment

The combination of NI LabVIEW system design software and reconfigurable I/O (RIO) hardware helps small design teams with varied expertise develop demanding embedded applications in less time. Using this graphical system design approach, you can take advantage of the same integrated platform to program embedded processors and FPGAs for faster application development in industries ranging from energy to transportation, manufacturing, and life sciences.

LabVIEW system design software offers ultimate flexibility through FPGA programming, simplifies code reuse, and helps you program the way you think–graphically.



>> Accelerate your productivity at ni.com/embedded-platform

800 453-6202

NATIONAL INSTRUMENTS

CUSTOMER SERVICE AND SUBSCRIPTION INQUIRIES
National: 800-877-5230

International: 903-636-1115

E-mail: technologyreview@pubservice.com

Web: www.technologyreview.com/customerservice

MIT Records: 617-253-8270 (alums only)

Reprints:
techreview@wrightsmedia.com
877-652-5295

Technology Review
One Main Street, 13th Floor
Cambridge, MA 02142
Tel: 617-475-8000

The mission of *MIT Technology Review* is to equip its audiences with the intelligence to understand a world shaped by technology.

Technology Review, Inc., is an independent nonprofit 501(c)(3) corporation wholly owned by MIT; the views expressed in our publications and at our events are not always shared by the Institute.

De Technologia non multum scimus. Scimus autem, quid nobis placeat.

REPUBLIC OF TURKEY PRIME MINISTRY
INVESTMENT SUPPORT AND
PROMOTION AGENCY

R&D, Innovation, and Turkey's Technology Ecosystem

Over the past 13 years, the Turkish economy has more than tripled, achieving a gross domestic product (GDP) of $800 billion in U.S. dollars in 2014. This remarkable performance, a culmination of more than a decade of steady growth, resulted from a sound macroeconomic strategy combining prudent fiscal policies with major structural reforms.

An increase in both public and private R&D expenditures accompanied that growth, with the nation's gross domestic expenditure on research and development (GERD) increasing to $6.5 billion in 2013. While Turkey's business R&D spending as a percentage of GDP—0.95 percent in 2013—is below the European Union average of 1.26 percent, Turkey's leaders believe the country's average annual growth rate of 12.5 percent over the last decade will narrow that gap soon.

In fact, Turkey has set an ambitious target of reaching a GERD/GDP ratio of 3 percent by 2023, a goal that takes into full account the net positive impacts of technology, R&D, and innovation in achieving long-term economic and social development. To facilitate that effort, the Turkish government is actively working toward a structural transformation to help companies design, develop, manufacture, and sell higher-value products in global markets.

INCENTIVE TO INNOVATE

One catalyst for this transformation will be a range of support and incentive programs currently being prepared to greatly encourage the manufacturing of technology products. Among those offering such support and incentive packages are the Scientific and Technological Research Council of Turkey (TUBITAK), the Small and Medium Enterprises Development Organization (KOSGEB), the Ministry of Science, Industry, and Technology (MoSIT), and local development agencies.

TUBITAK, which advises the government on scientific matters, plays a leading role in improving Turkey's research environment. To that end, TUBITAK offers a rich variety of grant-based support programs designed to increase the number of Technology Development Zones (or "technoparks"), R&D centers, and related projects in Turkey, which, in turn, will ensure ongoing dynamic innovation in the coming years.

Technoparks: Turkey's Technology Development Zones

Turkey's technoparks were established to support the development and production of software and other technologies through effective cooperation among universities, research institutions, and the private sector. One prominent example is the ITU Arı Teknokent in Istanbul, which draws on the resources of nearby Istanbul Technical University, a 242-year-old institution that offers more than 30 engineering degrees.

The technoparks also aim to attract qualified foreign direct investment that will increase Turkey's R&D potential, allow technology transfer, and commercialize R&D projects and innovative ideas. As of June 2015, 3,325 companies in 61 technoparks employed 33,380 staff engaged in R&D and innovation activities, with software and information and communication technology representing the most active sectors.

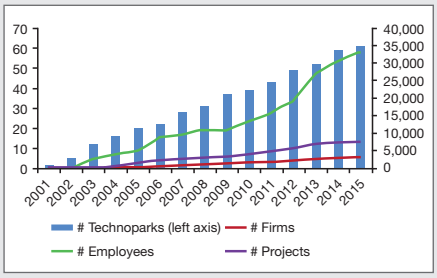
For more information, visit: invest.gov.tr

The ITU Arı Teknokent in Istanbul is among Turkey's 61 "technoparks."

Overview of Incentive and Support Programs

Republic of Turkey R&D Center Support	A company's R&D expenditures during a fiscal year are tax-deductible. An employee with a doctoral degree is subject to a 90 percent income-tax reduction. An employee with a master's degree is subject to an 80 percent income-tax reduction. Half of an employer's share of insurance premiums for R&D and support staff is covered by the Ministry of Finance for five years. New scientists can receive capital grants of up to TRY100,000 (about $37,000) for technology initiatives.
Scientific and Technological Research Council of Turkey (TUBITAK)	Grants cover all project-related expenses, including: • Overhead. • Travel. • Equipment, software, and publications. • Supplies and consumables. • Consulting from private and public sectors both in and outside Turkey.
Ministry of Science, Industry, and Technology (MoSIT)	MoSIT offers financial support via grants of up to 75 percent of a project's budget. Testing and laboratory services are provided by the universities where projects are being carried out.

Growth of Turkish Technoparks, 2001-2015



Source: Turkish Ministry of Science, Industry, & Technology

Feedback

E-mail letters@technologyreview.com

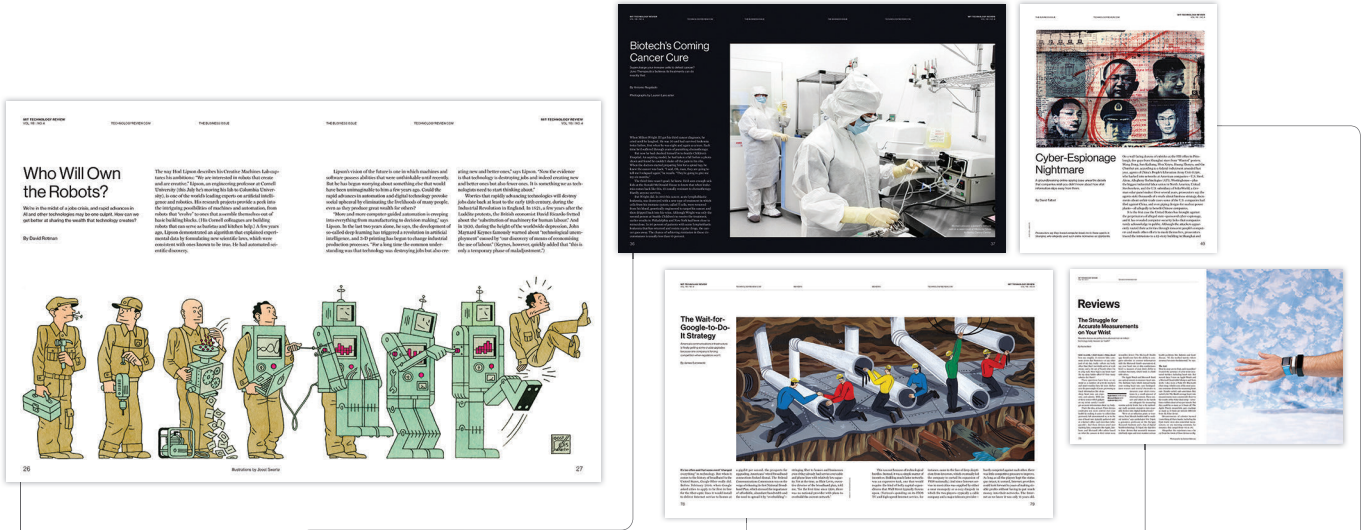
Write *MIT Technology Review*
One Main Street, 13th Floor
Cambridge, MA 02142

Please include your address, telephone number, and e-mail address.

Letters and comments may be edited for both clarity and length.

Five Most Popular Stories

MIT Technology Review
Volume 118, Number 4



1 Who Will Own the Robots?

One possible outcome is that people will adopt a protectionist stance against goods and services produced via highly automated processes. Instead, they will create and participate exclusively in markets for goods and services that maintain a significant human component throughout the production process (the new "organic"). People are clearly willing to pay more for sustainable products in the interest of preserving the environment. How much will they be willing to expend in the interest of preserving themselves?
—**QEV_N_NY**

2 The Coming Cancer Cure

Any approach that relies upon the immune system is going to have a lot of individual variability, and unfortunately, I suspect that many individuals in need of these treatments will have less than perfect immune systems going in. For now, it seems that this is far more of a niche treatment than a widely applicable approach. And of course, "curing cancer" in a general sense has always been a misnomer—it's not a single disease and there is not, therefore, a single cure. —**acowan**

3 The Wait-for-Google-to-Do-It Strategy

Here in India we may have pathetically slow Internet connectivity, but one thing we don't have is a monopoly or duopoly. In practically every part of the country we have something like six or seven service providers to choose from. This keeps the prices down. —**pmshah1946**

Take a look at the neighborhoods that Google Fiber is operating in. They are all areas of affluence that already had top-tier service with great speeds. Google isn't trying to "save broadband for the people." They are testing markets for profitability. —**mg1989**

4 The Struggle for Accurate Measurements on Your Wrist

In the case of diabetes, better testing via wearable sensors could relate to tighter glucose control, but this is a medical issue, not just a "health" issue, and once you cross the line to a medical issue, you are held to a higher standard. If the glucose reads 150 on a device when it's really 45 and the patient drives and crashes his car, the company can be held liable for making a defective device.
—**garygech**

5 Cyber-Espionage Nightmare

If we buy hardware from China, we may be purchasing spyware embedded into the hardware itself. Recently, the NSA has been accused of this. It would make sense for the Chinese to do it also. Back to the days of extranets?
—**wood.22mark**

Some of the remedies suggested sound useful, but none are feasible under current conditions. The very companies most vulnerable to the hackers might find reasons to keep doing business with a state actor such as China—what would their bottom lines look like without Chinese suppliers? —**ka5s**

Rethinking the Work Week

We should abandon the idea that everyone needs to work eight hours a day ("Who Will Own the Robots?" July/August 2015). The promise of technology has always been an increase in leisure, yet leisure time hasn't grown with the productivity gains brought by improved technology. Our goal should be to work as few hours as possible while keeping unemployment low and living standards high. Technology makes that possible—but only if we're willing to abandon antiquated assumptions about working hours and pay. **—golemme**

Wearables' Dirty Little Secret

After working for a company for five years leading efforts to develop wearable sensors ("The Struggle for Accurate Measurements on Your Wrist," July/August 2015), I can tell you that almost every company now marketing these wearable products is hiding serious flaws.

Accelerometer-based sensors are popular because they don't require contact with the skin. But while they're okay at counting steps, they're terrible with finer movements like breathing and heart rate, since they can't isolate them from the other vibrations all around us.

Optical sensors, used for temperature, heart rate, and oxygen levels, detect only surface temperatures and not core body temperature. Such sensors can supply garbage data if they're facing a window or if they're near an HVAC duct, a plasma TV, or a hot car.

Patches rarely work as claimed because of temperature changes, sweat, and just plain variance from human to human. Swallowable temperature sensors are accurate, but no one wants to swallow a sensor each day.

Think of it this way. Would you black out your car windshield and drive with only your Google Maps showing the road and turns? That's about the precision of today's wearables. **—DoesntWork**

Correction

The story "Fixing China's Coal Problem" in the Upfront section of our July/August issue contained an incorrect estimate of the amount of land affected by the coal industry in China. The industry affects thousands of square miles, not millions.

Views

John Killmer

Judith Donath

Richard Stallman

AGRICULTURE

Like GMOs, Minus the Baggage

Sprayed-on RNA can improve farmers' lives without genetically modifying their crops.

Almost 60 years ago I stood beneath a blazing Louisiana sun, up to my knees weeding in the tepid, mosquito-infested water of my father's rice field. It was the 1950s, and I was nine years old. I eventually got off that farm, but the experience made me devote myself to developing technology to make agriculture more productive and its practice less physically demanding.

Now I'm part of a company working to develop a new non-GMO technology that could provide a boost to agricultural productivity while also controlling insect-borne disease. Sprayed-on RNA that silences specific genes has the potential to transform agriculture for both large-scale and subsistence farmers (see "The Next Great GMO Debate," page 24).

So-called RNAi (RNA interference) technology could let farmers alter crops without permanent genetic modification. It could, one day, allow farmers to spray a crop with a drought remedy only when there's a drought. It could give them the ability to control mosquitoes in an environmentally benign way.

RNAi was not clearly described until the late 1990s, but research has moved rapidly. RNA is a natural component of all the food we eat, and there's good evidence that it's benign with regard to human health and the environment. Some even think it could be a great tool for organic farming, whose once-meteoric growth is now constrained by the lack of productivity tools common in large-scale agriculture.

A major impediment to all this is cost—manufacturing RNA is now incredibly expensive, and we need to find a cheaper way of making it. My company, APSE, is working on that problem now.

Genetic modification has been limited to a few crops and has been rejected by large swaths of consumers. Topical RNAi can provide many of the benefits that genetic modification has promised, but without the baggage.

John Killmer is CEO of APSE, a company developing RNA technology in agriculture.

WEB

Peer Pressure, Internet-Style

Live-streaming apps can subtly encourage you to give in to the demands of the crowd.

Live broadcasts have been a staple of TV since its earliest days. But new live-streaming apps such as Meerkat and Periscope change the audience from passive observers to active participants (see a profile of Meerkat creator Ben Rubin, page 44). With these apps, the audience makes comments that appear in the video stream, and the broadcaster decides how those comments affect the live events. What you see on screen is happening now—and you can affect the future. We need to be prepared for the new dynamics.

Imagine going shopping and asking your audience what glasses to buy. You could ask them how to arrange your furniture. You could take a tour and stop to peer at whatever the audience requests.

These scenarios involve trust: you're hoping the audience is on your side. But, this being the Internet, trolls are inevitable. More subtly, something about the dynamics of a remote audience seems to inspire otherwise reasonable people to cause trouble.

This problem was exemplified in a 2001 experiment we conducted at the MIT Media Lab. The setup was that an

ANDY FRIEDMAN

APPLICATIONS OPEN

LEMELSON-MIT STUDENT PRIZE

Recognizing the country's most outstanding collegiate inventors

Carl, MIT
2015 "Cure it!"
Grad Winner

"Cure it!"
for healthcare

Stephen and Joseph
Western Michigan Univ.
2015 "Cure it!"
Undergrad Winners

"Drive it!"
for transportation

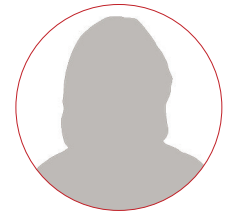
Josh, MIT
2015 "Drive it!"
Grad Winner

"Eat it!"
for food and agriculture

Alexander
NC State Univ.
2015 "Eat it!"
Grad Winner

"Use it!"
for consumer devices

Justin and Kevin
Penn State Univ.
2015 "Use it!"
Undergrad Winners



2016 Winner?

Do you know the next Lemelson-MIT Student Prize Winner?

Encourage a student inventor to apply now at lemelson.mit.edu/studentprize.

LEMELSON-MIT

actor equipped with a camera and a backpack full of electronics would do whatever the audience (the "directors") collectively decided she should do. Directors could suggest and vote on actions; every few minutes the highest-rated one would be sent to the actor to carry out. She ended up dancing on the table and eating from other people's plates. Suggesting something transgressive was irresistible.

You might think that in ordinary circumstances we'd feel free to ignore ridiculous suggestions. But our implicit contracts with our audience complicate things. Even when the audience's comments are ignored, the remote chorus changes the social dynamics.

Remote audiences are already influencing daily life. Many teens broadcast their days and their dates to a murmuring, texting crowd of kibitzing friends—relieved they don't live in their parents' lonely world, where most experiences are faced alone, unbuffered by a team of virtual advisors. It's not yet the norm to livestream much of your life and to wonder who is directing the words and reactions of the people around you. But that world is coming soon, to a screen near you.

Judith Donath is a Harvard Berkman faculty fellow and former director of the MIT Media Lab's Sociable Media Group.

POLICE REFORM

Controlling When the Cameras Record

If we're going to require body cameras, we need to be smart about when they're used.

Around the U.S., the agents that control the public have been observed to beat up, shoot, kill, and arrest members of the public, with a special focus on protesters, members of minority groups, and people making recordings of the actions of those agents. This is often followed by fabricated accusations against the victim, meant to create false justification for the attack itself.

To control these abuses, parts of the U.S. have begun ordering these agents to wear body cameras. Body cameras help restrain agents' violence but create problems of their own. For instance, when should the cameras record?

There are occasions when the cameras should be off, including confidential discussions that are important not to record. Sometimes agents are invited into homes; it would be intrusive for them to make video recordings of everything visible inside the home, because the recordings might be studied later for signs of anything that could be prosecuted.

However, if agents can turn their cameras off, they might do so precisely when they are going to commit violence, as appears to have happened in February 2015.[1]

I propose a technical system to control when these cameras record, removing most of the agents' discretion.

The idea is that the system records its camera's video (and its microphone's audio) all the time, but normally discards all recordings 10 minutes after they are made. Certain events (let's call them "significant events") cause those 10 minutes of recording to be saved, and the following 10 minutes as well.

Each agent's system detects certain significant events automatically. An agent can also manually declare a significant event by pushing a button. Either way, when one agent's system detects a significant event, it sends a radio signal to report the event to the systems of all agents within a certain reception distance—perhaps 50 meters.

Here are proposed criteria for detecting a significant event:

(1) Whenever the agent removes a gun from its holster. (2) Whenever the agent takes a weapon in hand to use it, including guns, tasers, sticks, and others. (3) Whenever the agent pushes a button to declare an event. Agents should be trained and required to do this when they see a violent attack or an injury, and then to aim their cameras at least briefly toward whatever they saw. (4) Whenever the system's microphone detects a gunshot.

The particulars of each significant event should be posted promptly on a website so citizens can verify that they are not being watched without grounds. An agent who pushes the significant-event button or draws a weapon without good reason should be punished enough to make such abuses rare, and those recordings should be deleted.

Another pertinent question is when the recordings should be made available to agents, prosecutors, a court, or the public. I propose that recordings saved because of a significant event should be made available only when a judge rules that they cover part of an act of violence, or in response to a subpoena about a specific person who appears in a specific video. In particular, agents would have to wait for court approval[2] to view the videos of events they participated in, and that would come after they make statements about the events.

Richard Stallman leads the free software movement (fsf.org), which campaigns to give users control over their programs. He led development of the free/libre operating system GNU (gnu.org), typically used with the kernel Linux in the combination GNU+Linux.

1. http://www.stltoday.com/news/local/crime-and-courts/st-louis-police-video-at-heart-of-lawsuit-dismissal-of/article_f4c65142-f3be-57f1-a957-9f256fb02459.html
2. http://www.dailykos.com/story/2015/04/14/1377729/-California-passes-intelligent-legislation-preventing-police-from-viewing-body-camera-footage

AAAS SCIENCE & TECHNOLOGY POLICY FELLOWSHIPS

"AAAS S&T Policy Fellowships exposed me to knowledge to integrate policy and government perspectives into social impact design."

I HAD A MONUMENTAL EXPERIENCE. YOU CAN TOO.

— Krista Donaldson, Ph.D., Mechanical Engineering, Executive Branch Fellow, U.S. Department of State, CEO, D-Rev

MAKE A DIFFERENCE. TRANSFORM YOUR CAREER.

Apply your scientific analysis and technical knowledge to inform policy through assignments in the Legislative, Executive and Judicial Branches.

Stipends from $75,000 to $100,000. Applications due **November 1.**

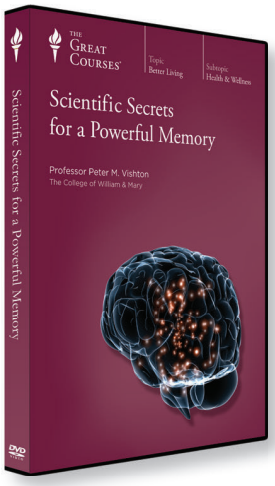
Details at: **aaas.org/stpf/MIT**

Enhancing Policy, Transforming Careers

SCIENCE & TECHNOLOGY POLICY FELLOWSHIPS
AAAS

THE GREAT COURSES®

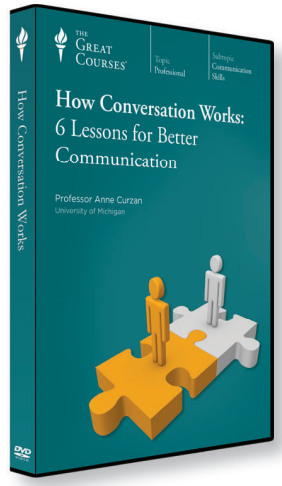
Improve Your Memory and Communication Skills with These Lessons You Can Take in Your Home or Car



Memory is the most powerful tool of everyday life. Memory gives you the power to plan, to reason, to perceive, and to understand. In **Scientific Secrets for a Powerful Memory**, you'll explore the real research on how memory functions—and then apply these findings to help you make better use of the memory abilities you have. You'll emerge with the ability to process information more effectively and to increase your chance of remembering almost anything.

Course No. 1965
6 Lectures
(30 Minutes/Lecture)

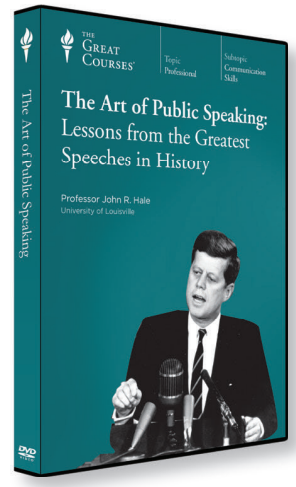
DVD COMPACT DISC DIGITAL DATA



One of the most important things you do on a daily basis is converse with others. Fortunately, it's a skill set anyone can acquire and refine. **How Conversation Works: 6 Lessons for Better Communication** will teach you key strategies that can dramatically improve your ability to speak with anyone, from strangers to supervisors. Focus on the fundamental principles you need to become more conversationally aware and savvy at home, at work, and beyond.

Course No. 9382
6 Lectures
(30 Minutes/Lecture)

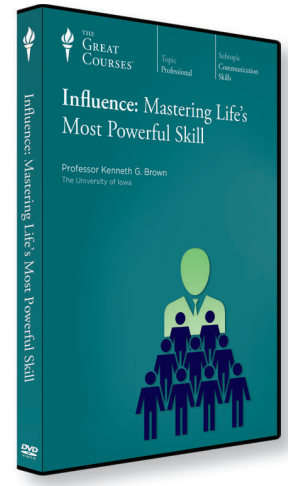
DVD COMPACT DISC DIGITAL DATA



Improve and enhance your public-speaking skills with time-tested techniques and strategies used by great orators in **The Art of Public Speaking: Lessons from the Greatest Speeches in History**. These 12 engaging and accessible lectures offer you helpful insights into preparing for public speaking, crafting a great speech, and handling your audience. Learn the secrets of what makes history's enduring speeches unforgettable, and speak better on any subject.

Course No. 2031
12 Lectures
(30 Minutes/Lecture)

DVD COMPACT DISC DIGITAL DATA



Whether you realize it or not, you're constantly surrounded by people and groups trying to influence you. You can actively take charge of your decisions by grasping the science behind how influence works. In **Influence: Mastering Life's Most Powerful Skill**, discover everything you need to tap into the hidden powers of influence and persuasion—and use them to enhance your personal and professional life in ways you never thought possible.

Course No. 5972
12 Lectures
(30 Minutes/Lecture)

DVD COMPACT DISC DIGITAL DATA

SPECIAL INTRODUCTORY OFFER!

Over 14,000,000 courses sold since 1990!
THE GREAT COURSES®

Order any one of these BEST-SELLING COURSES for only:

$9.95 on CD or DVD

+$5 Shipping and Handling
Priority Code: 116705

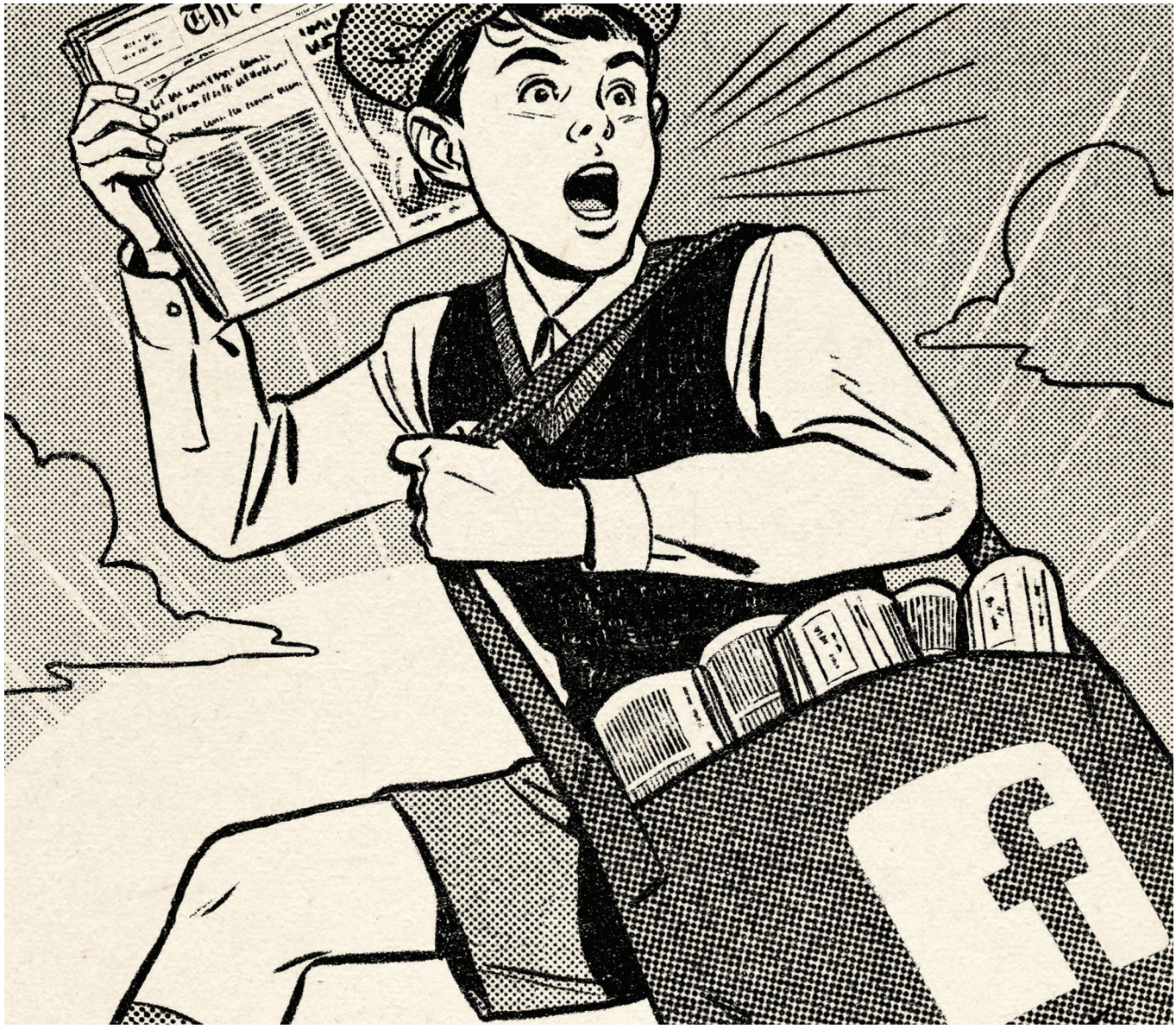
All orders subject to approval.
Limit of one order per household.
Cannot be combined with any other special offers or promotions.
Offer valid for new customers only.

LIMITED TIME OFFER
SAVE up to $190
ORDER BY OCTOBER 31

ORDER TODAY! Sale Ends Saturday, October 31, 2015!

www.THEGREATCOURSES.com/8TECH **1-800-832-2412**

Upfront



PATRICK LEGER

Facebook's Raw Deal for Publishers

Publishers like the *New York Times* should be having an existential crisis over Facebook's instant articles. Instead they're embracing them.

Here are some key numbers for content licensors in digital media: Netflix will pay approximately $3 billion in licensing and production fees this year to the television and film industry; Hulu is paying $192 million to license *South Park*; Spotify pays out 70 percent of its gross revenues to the music labels that hold the underlying

Upfront

rights to its catalogue. And then there's what Facebook is guaranteeing a variety of publishers, including the *New York Times*, BuzzFeed, and the *Atlantic*, who are posting articles in its new "instant articles" feature: $0. That's pretty much the deal being offered in other digital distribution agreements by Apple News and Snapchat Discover, and in an anticipated similar offering at Google. Nothing.

In effect, digital content is being divided between a lucrative high-end entertainment world, where licensors receive a negotiated fee for allowing the distribution of their property, and a low-end publishing world where content is expected to be "free," supporting itself on often elusive advertising sales and ad splits. In this particular deal, publishers can sell ads on their articles and keep all of the revenue, or have Facebook sell ads in exchange for 30 percent.

An important and grievous question is how this anomalous division in the media business came to pass. The more immediate question is whether Facebook's "instant articles" and other republishing initiatives are digging a deeper hole for publishers or helping them get out of the one they are already in.

Publishers of course believe the latter is true, or why else would they be doing such deals? On the other hand, publishers have largely found themselves in this dismal situation because of their past bad decisions—accepting the general free ethos, bowing to a vast catchall of casual and formal sharing and reposting agreements, and failing to challenge an ever-expanding interpretation of fair use. It seems only logical to doubt the business acumen of people who have been inept

Perhaps publishers are just shamefully bad businesspeople.

when it comes to protecting their interests in the world of digital distribution. Indeed, publishers continue to speak of the confounding transition to the digital world, but through another lens, it really needn't seem so difficult or foreign.

In the case of these new platform distribution deals, while they all involve slightly different plays, they each mimic a standard publishing business model: syndication. That is, a publisher with access to a different audience redistributes the content of another publisher—of course paying the content owner a fair fee.

In some sense, this is *the* basis of the media business. The *New York Times* has always syndicated its stories to other papers and, for nearly 40 years, to various electronic outlets. Cable operators pay to carry cable stations. Networks license shows and movies. Theaters pay studios. Content is valuable—otherwise, why distribute it?

There is, too, the reverse of this model, in which media buyers and other content creators pay distributors for access to their audience. That's called advertising. There is also a hybrid form of editorial and advertising content, such as free-standing inserts in Sunday papers, paid cable time, and native advertising online. In this format, you might try to create some sort of editorial (usually with a disclaimer in small letters that it is paid advertising content or some such), but the content is very much second to the products you're selling—it's pretend content.

When the Facebook "instant articles" deal was first proposed last fall, there was no provision at all for a financial exchange. From Facebook's point of view, it was just a further service to users and publishers. If it hosted the *Times'* content, it would load faster—providing a better experience for Facebook users clicking to a shared *Times* story. The *Times* and other publishers should do this, Facebook reckoned, because it would get them greater exposure to Facebook's vast audience.

After some limited pushback from the publishers, the deal now resembles a conventional digital ad split of the kind made ubiquitous by Google AdSense. That is, if Facebook sells against this content

TO MARKET

Shine a Light

Twist LED bulbs

COMPANY:
Astro

PRICE:
$399

AVAILABILITY:
Early 2016

A startup called Astro is adding small speakers to lightbulbs, which it thinks will make it easier to stream music wirelessly at home without requiring the use of more power outlets or counter space. Called Twist, the device is an LED bulb with a built-in speaker that uses Apple's AirPlay technology to stream music from iPhones, iPads, and Mac computers over Wi-Fi. Twist fits into a standard-size light socket and contains white and yellow LEDs, the brightness or dimness of which coördinates wirelessly with other Twist bulbs that contain just LEDs. Astro hopes to appeal to people living in small spaces, where they are often renting and may not want to install things like switches or wiring.

COURTESY OF ASTRO

through its networks, it splits the revenues with the publisher. If the publisher sells the ad, as though in a free-standing-insert model, it keeps what it kills. (Exactly the model that has always lowered digital ad prices—the inevitable discounting when you have many sellers of the same space.)

When I discussed this with one of the Facebook executives responsible for crafting the deal, I tried to point out that paying for content—i.e., traditional syndication—was exactly what kept the "content" from becoming advertorial. Otherwise, the content creator has to use this distribution opportunity to maximize sales potential—it's a singular monetization moment (the publisher is not building larger, sustainable brand value). The Facebook executive seemed mystified by why Facebook should care about this.

And indeed, it's a model that, on this monetization basis, might work to BuzzFeed's advantage. In a sense the "instant article" arrangement means BuzzFeed has cadged free space and free audience from Facebook, which it can sell back to clients sponsoring its content. This can work particularly well for BuzzFeed because it is not just an editorial organization but also effectively an ad agency (or direct response firm)—it strategically and shrewdly walks the fine line between editorial and promotion. (Certain print publication categories, like travel and fashion, have of course long straddled this line.) And that works just fine for both BuzzFeed and Facebook.

But what of the *New York Times*? It is not only that this syndication arrangement gives the *Times* no direct payments, but "instant articles" and other platform distribution deals move the business another step closer toward what Ken Doctor, an analyst and journalist who has closely covered the demise of the news business, calls "off news site" reading. In this model, publishers effectively give up their own channels and become suppliers of content to more efficient distribution channels. There is no *New York Times*, there are just *New York Times* articles—a distinction Facebook might not think much of but that all publishers, in this gradual relinquishing of their brand and audience, ought to have an existential crisis about. In effect, the *New York Times* becomes a wire service, like the AP, except that where the AP gets paid huge licensing fees, the *Times* does not. (In fact, the *Times* itself, reliant on the AP for its pictures and other reporting, will still be paying those fees to the benefit of Facebook.)

This is further puzzling because the *Times* has built a digital subscription business of almost a million users. Why subscribe to the *Times* if you can read it for free on Facebook?

Digital content from publishers is expected to be "free."

Of course, the subscription business alone will not support the *Times* (indeed, its growth appears to be seriously slowing)—it needs advertising too. Most of the advertising that pays for most of the *Times*' costs still comes from the actual newspaper. That revenue stream is declining quickly, however, and is far from being replaced by digital ads, which in the first quarter of 2015 yielded only $14 million a month in revenue (15 years ago, the *Times* was averaging more than $100 million a month in ad revenue).

These measly ad dollars are in part a function of the fact that Google and Facebook together take 52 percent of all digital advertising. In other words, part of the thinking here is if you can't beat 'em, join 'em—or submit to them.

From the earliest information-wants-to-be-free days of digital media, publishers have largely responded to the medium as an experiment, going forward because others were and because they "couldn't afford not to," scared into greater and greater urgency because they did not understand the technology. The ultimate result was a disastrous, sheep-to-slaughter endgame scenario, in which the new, digitally focused publishers are a fraction of their analog size.

And now, in the prevalent view, there is simply no turning back. The math has changed. The *New York Times* may once have made more than $100 million a month in advertising revenue on a 1.5 million circulation base; now it makes $14 million on 50 million monthly visitors on the digital side of the business. So it will need something like 350 million users to make equivalent money—which, bizarrely, Facebook might possibly provide. Except, of course, that the more the numbers go up, in digital math, the more their value goes down. But pay no attention to that.

Meanwhile, in another part of the media business, billions of dollars are now flowing to content creators and owners from digital platforms, with every major platform amping up negotiations with sports, television and film, and even music licensors. Sports and television and film have largely regarded digital deals as little different from their offline versions, scoffing at the idea of free. Even music, after many years of digital blackmail, has begun to wrestle back aspects of its business. (Thank you, Taylor Swift.)

There are of course differences between entertainment content and news and other editorial matter, and perhaps that accounts for why the old rules and basic business models that worked so well for so long should not apply in a digital context. Or perhaps publishers are just shamefully bad businesspeople.

—Michael Wolff

Upfront

Phablet Revolution

In India, bigger is better when it comes to mobile phones, but Apple is lagging behind competitors like Samsung and Xiaomi.

Zanish Khan runs a tiny shop in Delhi's Basrurkar Market, where India's middle class comes to buy life's essentials. All around him, other merchants offer everything from electric fans to dried lentils that shoppers can scoop from 100-pound burlap bags. By contrast, Khan's merchandise is kept under glass and packed with state-of-the-art electronics.

Still, Khan fits right in. India is in the midst of a smartphone buying binge, and Khan specializes in the oversized phone/tablet hybrids—or phablets—that enjoy great popularity in his country. His cases are stocked with models such as the Samsung Galaxy A5 and Grand 2, whose screens measure five inches diagonally. If that's not big enough, the Galaxy E7's screen stretches 5.5 inches. He hardly bothers stocking any phones with traditional screens of 4.5 inches or less.

Across Asia, smartphone buyers have decided that bigger is better. Market researchers at Flurry Analytics recently reported that 50 percent of smartphone sales in Taiwan and Hong Kong involve devices with screen sizes of five inches or more, versus a 20 percent share worldwide. A comparable study last year by Netbiscuits put India's phablet share at 29 percent. In Japan, Sony's biggest smartphone launches lately have involved phablets, while South Korea has been dubbed "the land of the phablet."

For Indian consumers with limited means, buying a phablet is a way of joining the digital era with a single purchase, says Anand Chandrasekaran, chief product officer at Snapdeal, a major Indian e-commerce company. The devices' large size makes them a bit awkward to use as phones, but devotees don't seem to mind. Overall, India is the fastest-growing smartphone market in Asia, with purchases running at a rate of more than 80 million a year. Cisco Systems recently predicted that Indians could own 651 million smartphones by 2019, up from 140 million last year. That's a boon for handset makers such as Samsung, China's Xiaomi, and India's own Micromax and Karbonn.

A phablet lets consumers join the digital era with just one device.

To date, Apple has won only 2 percent of the market in India. Local regulations make it impossible for Apple to set up its own sleek stores there, so it must sell through existing channels. Its most sophisticated offerings—such as the iPhone 6 Plus phablet—carry list prices approaching $1,000 in India, putting them beyond most buyers' budgets. Apple offers its older iPhone 4 at about $300, a strategy that has delivered mixed results. Some shoppers are thrilled to own anything made by Apple; others grumble about missing out on the newest designs.

But budget-minded customers have plenty of alternatives. Xiaomi made heads turn in January, when it launched its Mi Note phablet in India. It offered the device, with a 5.7-inch screen, for about $370. The initial allotment of Mi Notes sold out in three minutes online, having attracted 220 million preorders. Some would-be customers filled out dozens of order requests in hopes that at least one would be fulfilled. *—George Anders*

CHRISTOPH ABBREDERIS

PROFESSIONAL EDUCATION

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

YOUR DOOR TO MIT EXPERTISE & KNOWLEDGE

TRAINING & EDUCATION FOR PROFESSIONALS

Come to MIT for a Week

SHORT PROGRAMS

Register for a 1–5 day intensive course and gain critical knowledge to help advance your career and impact your company's success. Earn CEUs and a Certificate of Completion.

Each year approximately 40 courses are offered in a variety of subject areas (partial listing below):

- Biotechnology/ Pharmaceutical
- Computer Science
- Crisis Management
- Data Modeling and Analysis
- Design, Analysis, and Manufacturing
- Energy/ Transportation
- Imaging
- Innovation
- Leadership/ Communication
- Radar
- Real Estate
- Robotics
- Systems Engineering
- Sustainability
- Tribology

Come to MIT for a Semester

ADVANCED STUDY PROGRAM

Enroll in MIT courses through this non-matriculating, non-degree program. Participate on a full or part-time basis for one or more semesters. Apply by May 1 for Fall Term 2015.

As an Advanced Study Program participant you can:

- Advance your knowledge in the latest technologies and cutting edge research
- Choose from over 2,000 MIT undergraduate and graduate courses
- Earn grades, MIT credit, and a Certificate of Completion

Bring MIT to You

DIGITAL PROGRAMS

Interact with professionals from around the world without disrupting your work-life balance. Online courses are designed to advance your career at your own pace with a flexible schedule that meets the needs of a global workforce. **Register now and save 10% with code: TR10.**

Tackling the Challenges of Big Data	**Cybersecurity**
Oct 6 - Nov 17, 2015	Sept 15 - Oct 27, 2015
Nov 17 - Dec 29, 2015	Nov 10 - Dec 22, 2015
	Jan 12 - Feb 23, 2016

Visit: mitprofessionalxmit.edu

INTERNATIONAL PROGRAMS

Schedule regionally relevant MIT short courses in a global location near you today. MIT Professional Education will work with you to match your regional needs with relevant subject areas in the Short Programs portfolio.

CUSTOM PROGRAMS

Enhance your organization's capabilities and expertise through customized programs tailored to meet your specific corporate education needs and strategic goals.

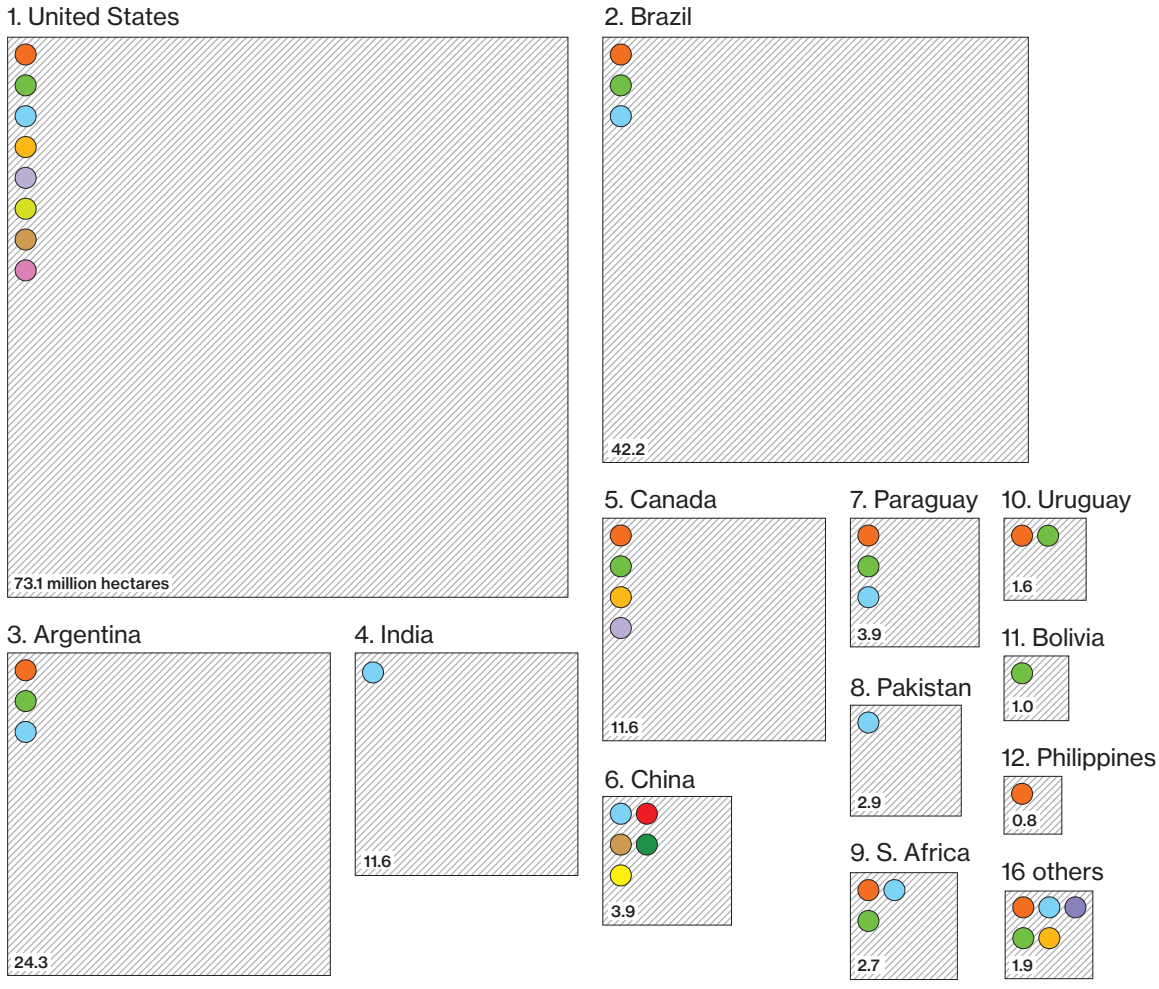
To learn more about what MIT Professional Education can offer you and your company, visit us today at **HTTP://PROFESSIONALEDUCATION.MIT.EDU/TECHREVIEW** or email us at **PROFESSIONALEDUCATION@MIT.EDU.**

Upfront

The State of Biotech Farming

More than 20 years after the debut of genetically modified crops, the majority of them are grown in just a few countries. But new technologies (see "The Next Great GMO Debate," page 24) and concerns about food security could change the landscape.

GMOs by Area
Countries just beginning to grow GM crops include Bangladesh, Vietnam, and Indonesia.



Crop Key

- Maize
- Soybean
- Cotton
- Canola
- Sugar beet
- Alfalfa
- Papaya
- Squash
- Poplar
- Tomato
- Sweet pepper
- Eggplant

Next-Generation GM Possibilities

Country	Crop	Function	Status
Kenya	Cassava	Enriched with iron, protein, vitamin A	In field trials. However, genetically modified crops are currently banned in Kenya.
Uganda	Banana	Resistant to bacterial wilt or to parasitic nematode and weevil	In field trials. GM crops are illegal in Uganda, though a pending bill would lift the ban.
India	Eggplant	Resistant to insect pests	Can be tested now that an effective moratorium on new GM crops has been lifted.
Philippines	Rice	Produces beta-carotene, a precursor to vitamin A	In field trials.
Argentina	Wheat	Drought tolerance	In field trials.

ILLUSTRATION BY LUKE SHUMAN; DATA ON CURRENTLY PLANTED CROPS COURTESY OF THE INTERNATIONAL SERVICE FOR THE ACQUISITION OF AGRI-BIOTECH APPLICATIONS; INFO ON NEXT-GENERATION CROPS COURTESY OF THE CORNELL ALLIANCE FOR SCIENCE AND RICROCH ET AL., CURRENT REVIEWS IN BIOTECHNOLOGY

24M Takes On Battery Industry

A startup from one of the A123 founders aims to overhaul the making of lithium-ion batteries—but it's not the first to try.

With more than $50 million in funding and five years of intense research and development behind it, 24M is ready to overhaul the lithium-ion battery industry.

Founded by MIT-based scientist Yet-Ming Chiang, the startup uses a novel battery composition based on a semi-solid material that eliminates much of the bulk of conventional lithium-ion batteries—which are typically made up mostly of inactive, non-energy-storing materials—while dramatically increasing their energy density. Chiang and 24M CEO Throop Wilder also say that they can reduce the time needed to make a battery by 80 percent and the cost by 30 to 50 percent.

If successful, 24M has the potential to drive the electric-vehicle market to a new level and accelerate the spread of renewable energy. But it faces a puzzle that many previous companies with promising technology have failed to solve: how to revolutionize a manufacturing industry with huge amounts of capital sunk into extensive existing capacity.

Chiang is personally familiar with this quandary: he was one of the founders of A123, the lithium-ion startup that received nearly $250 million in funding from the U.S. government, went public in the largest IPO of 2009, and filed for bankruptcy in 2012 after the EV market grew more slowly than expected and competition in the battery industry intensified.

Now, energy storage demand is soaring—for vehicles, for power grids, and for residences with distributed renewable generation, such as rooftop solar arrays. Capacity in the United States is expected to more than triple this year, and rapid growth will continue through the end of the decade, according to GTM Research. That means that demand for a less expensive, more efficient technology should be robust. But the building boom of the previous decade means there's also excess manufacturing capacity available to supply that market.

Meanwhile, the "gigafactory" Tesla is building in Nevada will dwarf any previous manufacturing ventures for lithium-ion batteries. And improvements in production processes for conventional lithium-ion batteries are reducing the cost of existing systems—even as research into next-generation chemistries, such as lithium-sulfur and lithium-air, continues at institutions around the world.

A lithium-ion battery from 24M.

In short, 24M is attempting to transform a worldwide manufacturing industry in which established players with deep pockets are investing heavily in the expansion of existing processes. That's a tough road even for a startup with a novel and exciting technology. Noting that 24M's modular plant design allows capacity to be scaled up as demand increases, its founders are undeterred. "This is the next great mega-market," Wilder says.

—Richard Martin

COURTESY OF 24M

QUOTED

"My goal is to obsolete that which I helped create."

—Alex Lidow, a semiconductor industry veteran whose company Efficient Power Conversion recently launched a line of chips made from gallium nitride, which is 10 times faster than silicon.

"My personal view is that every home will have a drone and every home will serve as an airport."

—Parimal H. Kopardekar, principal investigator of NASA's NextGen Airspace Project, an effort to build an air traffic control system that would, among other things, enable Amazon drones to drop packages on doorsteps.

"I can pinch again!"

—Panagiotis Polygerinos, a fellow at Harvard's Wyss Institute for Biologically Inspired Engineering, on the best response from a stroke patient wearing a soft robotic glove developed at Harvard to help people with limited hand mobility pick up objects.

BY THE NUMBERS

17 million

Number of cubic meters per day of natural gas China is expected to extract by the end of the year, compared with 1.3 billion daily in the U.S.

14

Number of accidents Google's self-driving cars have had after one million miles of travel.

$445 billion

Cost of data breaches to global companies in 2015.

4

Number of newborns to have their genomes sequenced in the BabySeq project, which measures the effectiveness of gene testing for infants.

Upfront

The Cancer Test Experiment

New diagnostics can find the DNA that drives a tumor, but evidence that liquid biopsies help patients is missing.

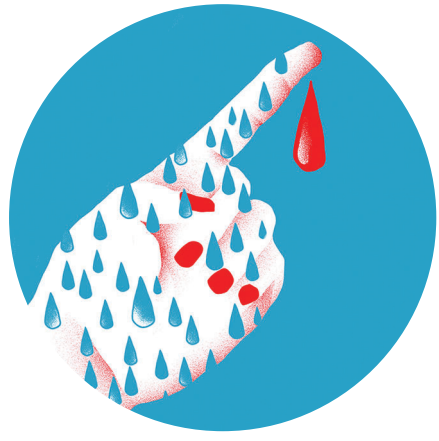
A year ago I interviewed Deborah Fletcher, a 54-year-old woman who was fighting inflammatory breast cancer. Like many patients with advanced cancer, Fletcher eventually put her hopes in an experiment. In her case it wasn't a new drug but a new kind of test, called a liquid biopsy.

The test scans a person's blood for small fragments of DNA released by tumors (see "10 Breakthrough Technologies," March/April). The one she got, from Guardant Health, a California startup heavily financed by venture capitalists, looks for the DNA sequences of 68 well-known cancer genes and can reveal the mutations driving a person's cancer. Fletcher hoped these clues would lead her doctors to pick the right drugs and cure her. She had her tumor's DNA profile taken six times and switched drugs twice. It wasn't enough: she died in May.

Fletcher's case is important because she was at the vanguard of what amounts to a global field study of the new DNA tests. Since laboratory diagnostics are regulated lightly in the United States, these tests have gone to market without consensus about their accuracy or data showing that they really help patients live longer. Tycho Peterson, an analyst at J. P. Morgan who tracks the industry, estimates $20 billion a year in tests globally by 2020, up from about $100 million today. So far most insurers, including Medicare, don't pay for them, because they don't think it's their role to underwrite what looks like a research experiment.

Eventually, the most important use of liquid biopsies should be to catch signs of cancer early, before symptoms arise—when a surgeon can cure it by cutting it out. Such screening could profoundly reshape cancer medicine. For now, though, they are being used as "theragnostics"—that is, tests that guide decisions about treatment. If doctors can spot a patient's key mutation, they can pick one of about 50 drugs designed to work directly against specific DNA defects. This is up sharply from 15 drugs in 2008.

Guardant's test, launched a year ago, was the first liquid biopsy to be offered



to doctors in the United States. It costs around $5,400. Since then at least eight other tests have been commercialized.

Whether DNA tests really help patients when they're used to guide treatment is a matter of dispute. Experts say large, controlled studies will be needed to find out. The American Society of Clinical Oncology recently said it would launch a clinical trial of a dozen targeted drugs to see how they work when their use is guided by DNA tests. The National Cancer Institute said it would launch a similar study of 20 drugs.

Meanwhile, some patients have started directly seeking out doctors using the newest tests. One of those people was Fletcher. She approached Massimo Cristofanilli, an oncologist at Thomas Jefferson University in Philadelphia, whose work had been featured on a radio program Fletcher heard. Cristofanilli was surprised to learn that her breast had last been biopsied a year earlier, explaining to her that cancer keeps changing.

Cristofanilli ordered two blood tests, which returned the same result: there was a new mutation in a gene called *PIK3CA* that he believed was making Fletcher's cancer cells resistant to Herceptin, the drug she had been taking. So he switched her to a different drug. After a second blood test showed that the new mutation was gone and a different one had cropped up, she went back on Herceptin. At first, the angry red lumps on her left breast shrank so much that her case was featured in a medical report.

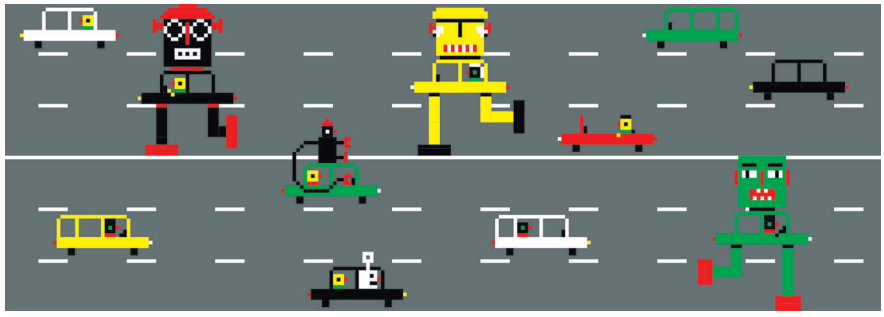
Cristofanilli says doctors in his clinic order more than 100 DNA tests every month; that's a bill of half a million dollars. But the cost seems acceptable to him. A bottle of Herceptin costs $70,000 a year—a lot to pay if it isn't helping. "We want to interrupt some treatments, start others, and keep up with the ever-changing biology of the disease. I think that is the future," he says.

By last October, Fletcher's cancer was getting worse again. Cristofanilli was out of new drugs to try. Fletcher decided to move from Virginia to Florida to be near her parents. Her mother says she looked around for trials of experimental drugs but never found one to join.

Fletcher had come to Cristofanilli with a very serious cancer, but he says he can't be sure the tests and drug switches helped her. "I do not think we have the data yet to show an extension of life," he says.

—Antonio Regalado

DANIEL ZENDER



Somewhat Driverless Cars

One software startup is taking a different approach to the automation of driving.

Some luxury cars can already drive unassisted in certain situations: neatly pulling into parking spots, for instance, or taking control in slow-moving traffic by following the car in front. But even as greater automation races to market, some are asking whether handing over control entirely to the machine is really the right approach.

A startup based in Cambridge, Massachusetts, called nuTonomy, is developing automation that's designed to feel more natural to drivers and can be combined with human control more effectively. Whereas a conventional self-driving car's computer system will plan an ideal route using radar, lidar, GPS, and other sensor data, algorithms developed by nuTonomy mimic the way a human drives, identifying a safe corridor to travel through. A car controlled by the company's software will drive the optimal path through this corridor. It's also possible to merge human and computer control more fluidly using the company's approach. The system can, for example, monitor a driver's steering, intervening only if it seems that he or she is about to veer outside the corridor defined by the software.

Automation in cars has been around for decades—adaptive cruise control has been standard since the 1990s, and automatic parallel parking was introduced in the early 2000s. But recent advancements have been spectacular. The newest BMW 7-Series, for instance, lets a driver step out of the car and have it park itself in a garage at the push of a button. Some Mercedes models can automatically follow the car in front in slow-moving traffic, and both Audi and Volvo plan to introduce such technology in the next year. Regulation mandating more use of automation is likely to follow.

Important milestones will come this year and next with the introduction of technology that lets cars automatically take over driving on highways. The electric-car maker Tesla has said it will issue an update for its Model S sedans, giving cars with the necessary sensors the ability to take control of speed and steering on highways. Cadillac plans to offer similar technology as an optional extra on some models next year.

The introduction of these systems could raise concerns about driver distraction, especially if drivers suddenly need to retake the wheel. Cadillac hasn't yet said how a driver will hand over or retake control from the system, but Dan Flores, a GM spokesman, says: "Rest assured, system failure scenarios are being comprehended in the development."

Greater automation is being propelled by interest not only from automakers but also from technology companies. Besides Google and its driverless car, Uber has signaled its interest in self-driving technology by poaching academic researchers with expertise in the area from Carnegie Mellon University, and even Apple is now rumored to be developing automated-driving technology. *—Will Knight*

TO MARKET

Exoskeletons in the Warehouse

AWN-03 Power Assist Suit

COMPANY:
Panasonic

PRICE:
$8,158

AVAILABILITY:
September

TIBOR KARPATI; PHOTO COURTESY OF PANASONIC

The Japanese company Panasonic sells an exoskeleton designed to help workers lift and carry objects more easily and with less risk of injury. The suit weighs just over 13 pounds and attaches to the back, thighs, and feet, enabling the wearer to carry 33 pounds of extra load. Sensors activate a lightweight carbon-fiber motor when the wearer is lifting or carrying an object. Panasonic's device is among a small but growing number of exoskeletons available commercially—less fantastic and more cumbersome versions of a technology that's been a staple of science fiction. Suits like this one could make a difference for many manual laborers, especially as the workforce ages.

ILLUSTRATIONS BY LAURIE ROLLITT

The Next Great GMO Debate

Deep inside its laboratories, Monsanto is learning how to modify crops by spraying them with RNA rather than tinkering with their genes.

By Antonio Regalado

The Colorado potato beetle is a voracious eater. The insect can chew through 10 square centimeters of leaf a day, and left unchecked it will strip a plant bare. But the beetles I was looking at were doomed. The plant they were feeding on—bright green and carefully netted in Monsanto's labs outside St. Louis—had been doused with a spray of RNA.

The experiment took advantage of a mechanism called RNA interference. It's a way to temporarily turn off the activity of any gene. In this case, the gene being shut down was one vital to the insect's survival. "I am pretty sure 99 percent of them will be dead soon," said Jodi Beattie, a Monsanto scientist who showed me her experiment.

The discovery of RNA interference earned two academics a Nobel Prize in 2006 and set off a scramble to create drugs that block disease-causing genes. Using this same technology, Monsanto now thinks it has hit on an alternative to conventional genetically modified organisms, or GMOs. It can already kill bugs by getting them to eat leaves coated with specially designed RNA. And if the company succeeds in developing sprays that penetrate plant cells, as it's attempting to, it could block certain plant genes, too. Imagine a spray that causes tomatoes to taste better or helps plants survive a drought.

Monsanto isn't the only one working on genetic sprays. Other large agricultural biotech companies, including Bayer and Syngenta, are also investigating the technology. The appeal is that it offers control over genes without modifying a plant's genome—that is, without creating a GMO.

That means sprays might sidestep much of the controversy around agricultural biotechnology. Or so companies hope. What's certain is that a way to accomplish the goals of genetic engineering without having to develop a GMO could bring commercial rewards. Sprays might be quickly tailored to do battle with an insect infestation or a new type of virus. Not only could this be faster than creating new GM crops, but the gene-silencing effects of RNA interference last only a few days or weeks. That means you might spray on traits such as drought resistance in times of water shortage without affecting the plant's performance in times of normal rainfall.

Beattie showed me a large glass jar in which dried, purified RNA glistened like crumbled packing peanuts. A few years ago, this much RNA might have cost $1 million, one reason few would have thought to spray it from tractors rumbling through rows of corn. But the cost of making RNA has plummeted. Monsanto estimates that it now costs $50 a gram. A tenth that amount, the company says, is potent enough to kill 100 percent of beetles on an acre of plants.

At Monsanto I met Robb Fraley, the company's chief technology officer, who oversees a research staff of 5,000. Three years ago Fraley designated the RNA sprays as one of Monsanto's new areas for product development. He thinks that within a few years they will "open up a whole new way to use biotechnology" that "doesn't have the same stigma, the same intensive regulatory studies and cost that we would normally associate with GMOs." He's told people he thinks the tools are "incredible" and "breathtaking" and that "of all the platforms we are working on, this is the one that reminds me the most of the early days of biotech."

It was Fraley who made Monsanto's first GM plants in the 1980s—petunias resistant to a plant poison. Today, Monsanto has revenues of about $9 billion a year from GM seeds for crops that produce the insect toxin Bt or resist the weed killer Roundup. GM corn, soy, and cotton plants now spread across 180 million hectares (see page 20). And it has generated a public controversy just as vast. To its strongest critics, the company is simply "Monsatan."

But with the RNA spray technology, which Monsanto calls BioDirect, the company may have found something that will bedevil opponents. The sprays are made from a ubiquitous molecule that degrades quickly in soil. They can be genetically precise enough to kill potato bugs but spare their ladybug cousins. And so far, consuming RNA molecules appears no more toxic to people than drinking a glass of orange juice. As Monsanto put it in a letter to U.S. regulators, "humans have been eating RNA as long as we have been eating."

Public opposition, regulations, and the slow pace of plant breeding mean that on average, bringing a new GM crop to market costs more than $100 million and takes around 13 years. But imagine you wanted to fight a plant virus, says James Carrington, head of a Missouri nonprofit called the Danforth Plant Science Center and an advisor to Monsanto. "If you can gain control with a spray, you can envision a product that can change very rapidly, that you can test faster, experiment with faster, and bring to market faster," he says. "You could respond to issues as they arise."

Not everyone is convinced, though, that applying RNA will be commercially feasible or any less controversial than genetic modification. "The public is not accepting GMOs, and this could be more alarming. People are going to say you are taking the RNA and spraying this in the open," says Kassim Al-Khatib, a plant physiologist at the University of California, Davis. "The acceptance of biotech has to be there before you can deliver another approach. This isn't a technology for tomorrow. It's for the day after tomorrow."

When I met Fraley, he didn't deny that there are obstacles—in fact, that's what reminds him so much of biotech's early days. He says no one yet understands exactly how to get RNA inside a plant's cells using a field sprayer—at least not with the sort of inexpensive, works-every-time efficiency farmers would be looking for. Many insects are also not easily affected. Monsanto has been spending millions to crack these problems, collaborating with biotech companies specializing in drug delivery. "We're still a few breakthroughs away," he says.

Weed control

The cells of plants and animals carry their instructions in the form of DNA. To make a protein, the sequence of genetic letters in each gene gets copied into matching strands of RNA, which then float out of the nucleus to guide the protein-making machinery of the cell. RNA interference, or gene silencing, is a way to destroy specific RNA messages so that a particular protein is not made.

The mechanism is a natural one: it appears to have evolved as a defense system against viruses. It is triggered

when a cell encounters double-stranded RNA, or two strands zipped together—the kind viruses create as they try to copy their genetic material. To defend itself, the cell chops the double-stranded RNA molecule into bits and uses the pieces to seek out and destroy any matching RNA messages. What scientists learned was that if they designed a double-stranded RNA corresponding to an animal or plant cell's own genes, they could get the cells to silence those genes, not only those of a virus.

Some GM plants already use RNA interference to disable unwanted enzymes, or to kill viruses or pests. The Flavr Savr tomato—the first genetically modified crop to be approved in the United States, back in 1994—harnessed the mechanism to block an enzyme that makes tomatoes soft, so they could ripen longer on the vine. Like Monsanto's Roundup Ready cotton and corn, the Flavr Savr was a GMO. Its seeds have an extra gene that manufactures a specific RNA molecule. Since then, companies have engineered a few other plants to take advantage of RNA interference. This year a Granny Smith apple genetically modified to silence a gene that turns apple slices brown won clearance from regulators. Before that, the Hawaiian papaya industry was saved by plants engineered to produce RNA that defends against the ringspot virus. And Monsanto is awaiting approval to sell corn plants that use RNA interference to kill the western corn rootworm. That plant is the first GMO to incorporate an insecticidal RNA into its genetic makeup.

But what if you could just spray the RNA on instead of tinkering with a plant's genome? A chemist named Doug Sammons was the first person inside Monsanto to have the idea. He studies weeds that have become resistant to glyphosate, the herbicide that Monsanto markets as Roundup. These weeds have become a huge problem for farmers and for Monsanto. Sammons determined that some resistant weeds have as many as 160 extra copies of a gene called *EPSPS*. That's the very enzyme glyphosate interferes with, blocking plant growth. The super-weeds had found a trick to overwhelm the herbicide.

Sammons thought the weed's extra genes could be knocked back into line with RNA interference. The problem was that since weeds are wild, Monsanto didn't have any way to control their genetic makeup, as it could with a corn plant. "So he came to us and said, Why don't we just spray it on a plant? We were like, 'Really?'" says Gregory Heck, a research manager at Monsanto. "We'd only thought of [GMOs] until that time."

Left: A Colorado potato beetle. Center: Oranges affected by citrus greening disease. Right: A jar of purified RNA on display at Monsanto.

It seemed unlikely to work—but it did, according to Monsanto. In lab tests and at a roadside plot in Illinois that's been overrun by weeds, a mixture of Roundup and double-stranded RNA coded to match the *EPSPS* gene made resistant weeds wilt. According to Monsanto's patents, the technique also involved spraying a silicone surfactant that let the RNA molecules slip into air-exchange holes in the plant's surface. Somehow, soaking the leaves with RNA caused the silencing effect to spread through the entire plant, affecting it long enough to let the herbicide take hold.

The technology could give Monsanto a new, exclusive formulation of Roundup (which lost its original patent several years ago) and help deal with the troublesome weeds, which have spread across U.S. farmland. "It's definitely a prize if you can reënable glyphosate," says Heck. But the

COURTESY OF DWIGHT SIPLER/FLICKR; COURTESY OF MCLEAN PHOTOGRAPHY; COURTESY OF MONSANTO

company's scientists saw that it could do much more: they could theoretically reach in and temporarily block any gene in any crop. "It could be a weed or a corn plant," says Lyle Crossland, a senior program manager at Monsanto. "You could just dial in the sequence information. You could turn off the gene that makes fruits brown; you could do something with drought tolerance, photosynthesis. We have a lot of probing going on."

Some plant experts aren't convinced it's practical yet. Stephen Powles, director of the Australian Herbicide Resistance Initiative and a professor at the University of Western Australia, told me he'd had a "bit of a go" at repeating Monsanto's weed experiment but hadn't been able to make it work. "Getting double-stranded RNA sprayed onto plants and getting it into plants, and killing a plant, is not easy, and in fact it's very, very difficult," he says. "There's the formulation technology, the shelf life, and can it bounce around in the back of a pickup for a week at 110 °F."

Richard Jorgensen, a plant biologist who was the first to observe RNA interference, thinks modifying traits with a spray "might be really patchy" compared with a true GMO. Say you wanted to turn flowers a specific color. "Would you spray it every week and hope it gets into every cell in the plant bud? I think there are lots of limitations compared to [GMOs]," he says. To Powles, however, the idea of spray-on traits has strong appeal. "It's a way of elegantly targeting particular genes and turning those genes off. And there are undesirable trait genes in everything," he says.

Skunk works

After the weed discovery, which occurred in 2010, Monsanto began spending heavily to build a position in RNA technology. It took over a company called Beeologics, which had found a way to introduce RNA into sugar water that bees feed on in order to kill a parasitic mite that infests hives. That company had also come up with a much cheaper way to make RNA.

Monsanto also began trying to crack the problem of getting RNA into plants more efficiently. It paid $30 million for access to the RNA interference know-how and patents held by the biotech company Alnylam, and it did a similar deal with Tekmira, an RNA delivery specialist based in Burnaby, British Columbia. Monsanto is also the financial backer of a 15-person company called Preceres, a kind of skunk works it established just off the campus of MIT, where robotic mixers are busy stirring RNA together with coatings of specialized nanoparticles.

The startup was created by drug delivery specialists, including MIT professors Daniel Anderson and Robert Langer, who have spent a decade learning how to get RNA drugs into human cells—a problem so difficult it almost derailed the idea of such medicines. Anderson told me the crop project faces substantial difficulties, too. "It's easier to envision if you are injecting a person in their veins, but if you are spraying out of a plane, that would be a whole different set of challenges," he said. "We don't have to worry about wind currents with drugs."

The basic task at Preceres is how to get a large, electrically charged molecule like RNA to move through a plant's waxy cuticle and into its cells. To do it, researchers there are working to encapsulate the RNA in synthetic nanoparticles called lipidoids—greasy blobs with specialized chemical tails. The idea is to slip them into a plant, where the coating will dissolve, releasing the RNA. Formulations get shipped out to St. Louis for testing in greenhouses.

Roger Wiegand, the company's CEO, says the company is also trying to kill insects that aren't as easily affected by RNA as the potato beetle. "There are insects that just laugh at naked double-stranded RNA," he says. Those include a caterpillar now infesting Brazil's soybean crops. He says some of the formulations get tested for endurance in caterpillar spit that Monsanto sends to Cambridge.

If they are able to sort out the delivery problems, Wiegand thinks, RNA sprays will be "a big frickin' deal" and "a breakthrough at the same level GMO plants were." Yet so far, only a few scientific publications even mention the idea of RNA sprays. That makes it hard to judge companies' claims. And many aren't talking at all. Bayer declined to comment on its research program. So did Syngenta, which in 2012 paid $523 million to acquire

Monsanto has spent millions learning how to control plant traits using genetic sprays. Opponents see a new risk.

Devgen, a European biotech with which it had worked on RNA insecticides.

One project I did learn about is led by Nitzan Paldi, an Israeli entrepreneur who'd been a cofounder of Beeologics. His current startup, called Forrest Innovations, is investigating a solution to citrus greening disease, a blight that's destroying Florida's citrus industry and is also present in Brazil. Caused by bacteria spread by an invasive insect called the Asian citrus psyllid, it leaves oranges hard and discolored, with juice the flavor of jet fuel. Last year, 22 percent of oranges in Florida suddenly fell off the trees.

Paldi isn't willing to disclose exactly how he's applying the RNA, but he did say he's hoping to block genes involved in the trees' reaction to the bacteria. It's their immune response to the infection that causes the greening symptoms. If the treatment works, Paldi believes, an RNA intervention could sail past regulators. With growers desperate, and the prospect of no more Florida orange juice, the public may be open-minded too. "We are potentially riding in on the horse and saving the day," he says.

Killer match

At Monsanto, the effort to develop an RNA spray to kill potato beetles has overtaken the weed idea. It could reach the market by 2020, says Jeremy Williams, a Monsanto geneticist who directs the insect program. The company has settled on a gene target and has begun efforts to make the spray rainproof so it grips the plant leaf and doesn't wash away for at least a week.

One reason the potato beetle is an interesting target for RNA sprays is that it's famous for becoming resistant to conventional insecticides. Since 1952, it's developed resistance to more than 60 of them, starting with DDT. But RNA interference is a means of attack that Williams doesn't think will be easy to overcome. If the beetle does evolve to resist an RNA molecule, he says, geneticists could easily launch a new assault: just "slide the sequence over" by a few letters or target several genes at once.

Monsanto has also been interested in the problem facing orange growers. It collaborates with Wayne Hunter, a spiky-haired entomologist at the U.S. Department of Agriculture's research laboratory in Fort Pierce, on Florida's Atlantic coast, where grapefruit and orange orchards are affected by citrus greening disease. With assistance from Monsanto, Hunter has been trying to kill the psyllid insect with RNA. He toured me through a plot of 100 orange trees, explaining that he'd drenched their roots with RNA or injected it into their trunks. Hunter's most interesting result is that orange trees seem to soak up double-stranded RNA and hold onto it. He applies a relatively huge dose to each tree, about 200 milligrams, and finds traces of the molecules still in their canopies three months later.

In Hunter's lab, psyllids were feeding on cuttings from trees resting in cups of liquid spiked with double-stranded RNA. Hunter was testing specific sequences that match crucial genes in the insect. One, which codes for arginine kinase, interferes with its ability to make energy.

Before picking a target, scientists can sift through online archives of DNA data to avoid matches with the genes of friendly insects, like honeybees. It takes an exact match of about 20 consecutive genetic letters for RNA interference to work. The resulting double-stranded RNA molecules, usually about 200 letters long, are then fed to other species, including bees, aphids, and whiteflies, as a practical test for "off target" effects. Monsanto has found that its sequences—which it calls triggers—usually don't affect any but the most closely related species, bugs in the same genus. "The differences are genetic," says Hunter. "The genes of insects are not identical. If it does not match, it does not kill."

In contrast, conventional insecticides wipe out helpful insects along with the bad ones. To stave off the greening disease, growers in Florida have been applying such chemicals as often as every two weeks. One, imidacloprid, is restricted in Europe for its suspected link to bee colony collapse. "We've just got to get away from hard-core pesticide use," says David Hall, leader of the subtropical-insect research unit that Hunter works in.

So far, it looks as though RNA treatments would be at best an adjunct in the orange groves, not a silver bullet. RNA doesn't knock bugs out instantly, as a chemical neurotoxin does. In Hunter's lab, insects only start dying after four days, and some live two weeks. "It's a biopesticide—it takes longer," he says. Perhaps partly for that reason, the field study of 100 trees supported by Monsanto yielded ambiguous results. The trees remained covered with psyllids, but they might have flown in from elsewhere. Hunter is planning to try again in a large enclosed greenhouse where he can apply RNA to every tree, mimicking what would happen if growers used an "area-wide" application.

Meanwhile, growers are trying anything. Some grind up infected trees. There is also a GM tree that's resistant to the blight, thanks to an added gene from a spinach plant. But even if consumers accepted GM orange juice, those trees couldn't be planted fast enough to replace the millions of

sick ones in Florida's groves. Hunter's RNA molecules probably won't arrive soon enough either. "We are still 10 years away," he says. "That is a problem with this technology. Around here, there is an enormous amount of pressure to come up with a solution."

Big questions

People on Monsanto's public relations staff told me they hoped to communicate better on RNA sprays than they had on GMOs. (Visitors to the company's offices can pick up a handout titled "12 Myths about Monsanto"; number 1 is the rumor that it bars GMOs from its own cafeteria.) Until now, the sprays have been too deep in the R&D pipeline to attract the attention of GMO opponents. But plants genetically engineered to use RNA silencing have drawn attacks. In 2012, the Safe Food Foundation in Australia alleged that experimental wheat developed by the Australian government could kill people. They said the RNA trigger designed to change the plant's starch content might match the gene for a human liver enzyme and interfere with it, too. The charge was fanciful, mostly because RNA does not appear to make it past a person's saliva or stomach acids. Even so, says Wiegand, "the big question any skeptic will raise is: 'If you are killing insects, what will this do to me?'"

Monsanto has been laying groundwork for the inevitable safety debate. It sent staffers to grocery stores and farm stands to collect fruits and vegetables that appeared to be suffering from viral infections. Analyzing these, they found thousands of fragments of viral RNA, many of which closely matched human genes. Yet it's not known that anyone has been harmed by RNA in produce. Given this "history of safe consumption," the company concluded, mere matches between RNA triggers and human genes have "little biological relevance."

Last year the U.S. Environmental Protection Agency asked a panel of experts to help it decide how to regulate RNA insecticides, including sprays as well as those incorporated into a plant's genes. In an 81-page letter to the agency, Monsanto lobbied against any special rules. It said RNA products should actually be spared safety tests it called irrelevant, including those designed to assess whether they were toxic to rodents and whether they could cause allergies, as well as in-depth studies of what happens to the molecules in the environment. Only proteins cause allergies, Monsanto said. And when the company doused dirt with RNA, it degraded and was undetectable after 48 hours.

Company research probably won't ever satisfy critics. The National Honey Bee Advisory Board told the EPA that using RNA interference at this point would put natural systems at "the epitome of risk" and could be as regrettable as our earlier embrace of DDT. "We are decades away from enough scientific understanding to allow sustainable and predictable use of this technology under field conditions," they said. The beekeepers worry that pollinators could be hurt by unintended effects. They made the point that the genomes of many insects aren't yet known, so scientists can't predict whether their genes will match an RNA target.

The EPA's advisors, in their report last year, agreed that there was little evidence of a risk to people from eating RNA. But is there some kind of ecological risk? This question they found harder to answer. Monsanto paints RNA as safe and quick to disappear, yet the aim is to make it lethal to insects and weeds, and the company wants to develop longer-lasting formulations. How long? In Hunter's trees the molecules persisted for months. What's more, Monsanto's own discoveries have underscored the surprising ways in which double-stranded RNA can move between species.

These unfolding discoveries suggest that complex biology is at work, leading the EPA's advisors to say that the "potential scale" of RNA used in agriculture "warrants exploration of the potential for unintended ecological effects." RNA may be natural. But introducing large amounts of targeted RNA molecules into the environment is not. The advisory panel concluded that "knowledge gaps make it difficult to predict" exactly what problems might arise.

Yet the biggest challenge to RNA sprays, Nitzan Paldi told me, isn't going to come from regulators. The real problem can be summarized in a single word: Monsanto. "For half the world, that is enough to know it's evil," he says. "Monsanto is introducing a new technology, full stop. But Monsanto is also the best way to make this real. For the scientifically literate, this is the dream molecule."

Antonio Regalado is MIT Technology Review*'s senior editor for biomedicine.*

MIT Technology Review **Insider**

Insiders get exclusive discounts on MIT Technology Review **EmTech** November 2-4, 2015

Unique Experiences

Exclusive discount offers and preferred seating at all our events.

Insiders also enjoy ...

Exclusive Content

Get full access to print and digital content, including exclusive videos, interviews, features, and more.

Impassioned Community

The premier community of leaders and innovators who seek to understand and influence technology in the world around them.

technologyreview.com/GetInsider

35 Innovators Under 35 2015

There's more than one way to read these stories. Sure, the subjects are inspiring and creative people. But these are not merely personality profiles. They also illustrate the most important emerging technologies of the moment. In biomedicine, for example, we feature several people who are figuring out in detail how the brain works and how we might stave off mental disorders. Others are unearthing knowledge about cancer that might open new avenues for treatment. Meanwhile, as robotics and artificial intelligence make astonishing progress, innovators in those fields are showcased here. So are people who are cleverly taking advantage of the falling cost of sensors and bandwidth.

The selection process for this package begins with hundreds of nominations from the public, *MIT Technology Review* editors, and our international partners who publish Innovators Under 35 lists in their regions. Our editors pare the list to about 80 people, who submit descriptions of their work and letters of reference. Then outside judges rate the finalists on the originality and impact of their work; that feedback helps the editors choose this group.

NEXT YEAR
Suggest candidates for the 2016 list at technologyreview.com/nominate

JUDGES

Zhenan Bao
Professor of Chemical Engineering, Stanford University

David Berry
General Partner, Flagship Ventures

Edward Boyden
Co-director, MIT Center for Neurobiological Engineering

Yet-Ming Chiang
Professor of Materials Science and Engineering, MIT

James Collins
Professor of Biomedical Engineering, Boston University

John Dabiri
Professor of Civil and Environmental Engineering, Stanford

Tanuja Ganu
Cofounder, DataGlen

Javier García-Martínez
Director of Molecular Nanotechnology Laboratory, University of Alicante, Spain

Julia Greer
Professor of Materials Science and Mechanics, Caltech

Christine Hendon
Assistant Professor of Electrical Engineering, Columbia University

Eric Horvitz
Managing Director, Microsoft Research

Rana el Kaliouby
Chief Strategy & Science Officer, Affectiva

Hao Li
Assistant Professor of Computer Science, University of Southern California

Cherry Murray
Professor of Physics and Technology and Public Policy, Harvard University

Carmichael Roberts
Entrepreneur and General Partner, North Bridge Venture Partners

John Rogers
Professor of Chemistry and Materials Science Engineering, University of Illinois

Umar Saif
Vice Chancellor, Information Technology University Lahore, Pakistan

Julie Shah
Associate Professor of Aeronautics and Astronautics, MIT

Rachel Sheinbein
Managing Director, Makeda Capital

Leila Takayama
Senior Researcher, Google X

Kay Tye
Assistant Professor of Neuroscience, MIT

Sophie Vandebroek
CTO, Xerox

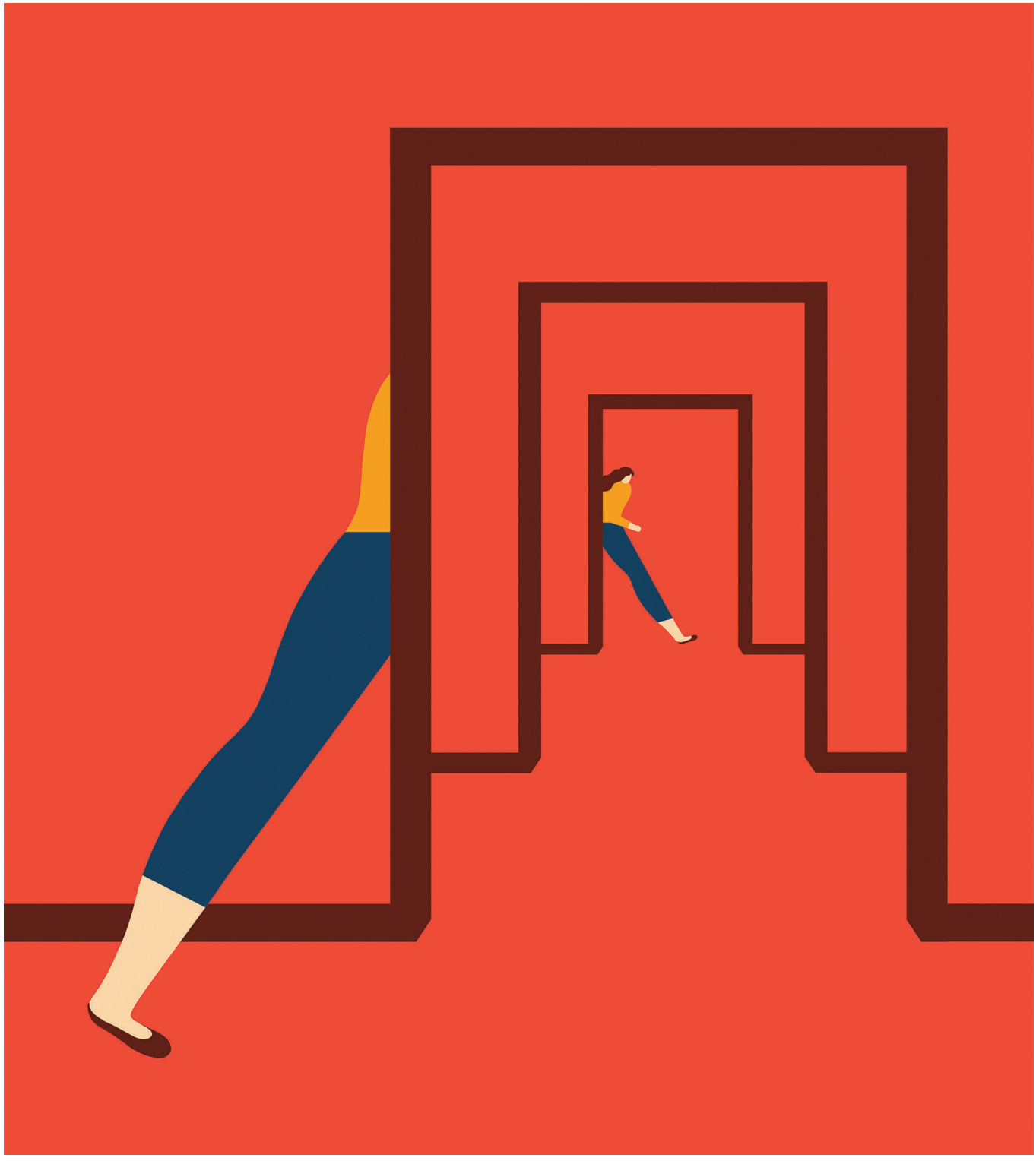
Jennifer West
Professor of Engineering, Duke University

Jackie Ying
Executive Director, Institute of Bioengineering and Nanotechnology, Singapore

Ben Zhao
Professor of Computer Science, UC Santa Barbara

Xiaolin Zheng
Associate Professor of Mechanical Engineering, Stanford

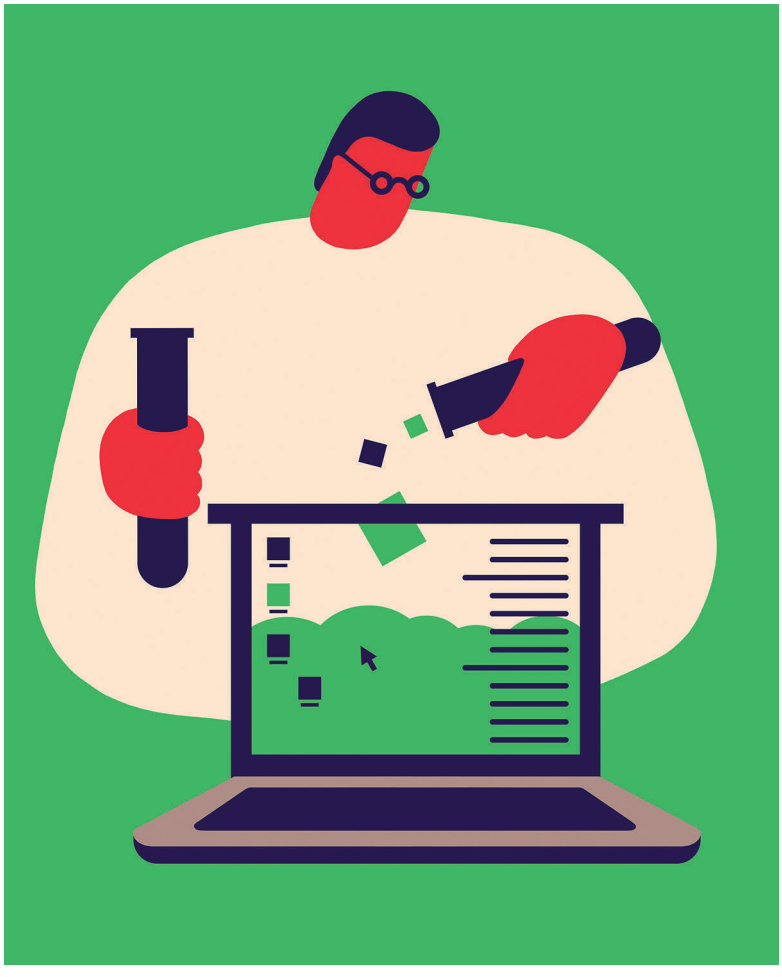
Color portraits by Matthew Hollister; black-and-white portraits by Ping Zhu



MAGOZ

Inventors

Creating technologies that make it possible to reimagine how things are done.



CANAN DAGDEVIREN

A master of flexible sensors and batteries sees opportunities for a new class of medical devices.

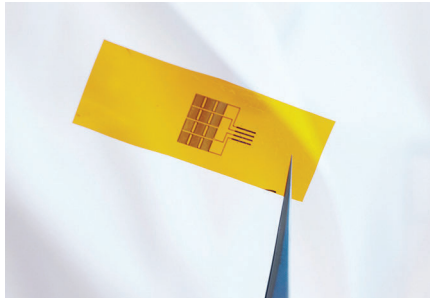
What do you do when your mother complains that she can't tell if her skin cream is working? If you're the Turkish materials scientist Canan Dagdeviren, you build a device that can measure changes in skin quality too slight to be detected by human touch. While working with dermatologists to develop the instrument, however, Dagdeviren found that it could be put to a more significant use: screening for skin cancer, either to catch it earlier or to help patients avoid unnecessary biopsies.

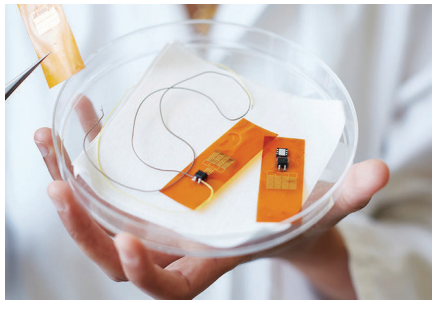
One early indicator of cancer is a patch of skin slightly thicker than the skin around it. It turns out that Dagdeviren's device, a tiny sensor and battery embedded in a translucent patch of stretchy rubber, can detect variations in skin density more accurately than a doctor's fingers. It can be pulled over skin anywhere on the body to take such measurements.

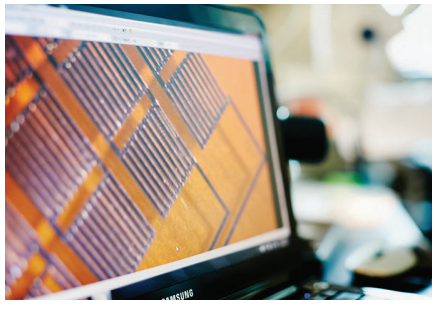
As a PhD student at the University of Illinois, Urbana-Champaign, Dagdeviren also developed a device that can be permanently implanted inside the body and harvest energy from the movements of organs. It can send that power directly to devices like pacemakers or be used to charge a battery. Today, pacemaker batteries are bulky and need to be surgically replaced every five to eight years. Dagdeviren's self-powering device, which has been tested in animals, could make life with a pacemaker that much easier.

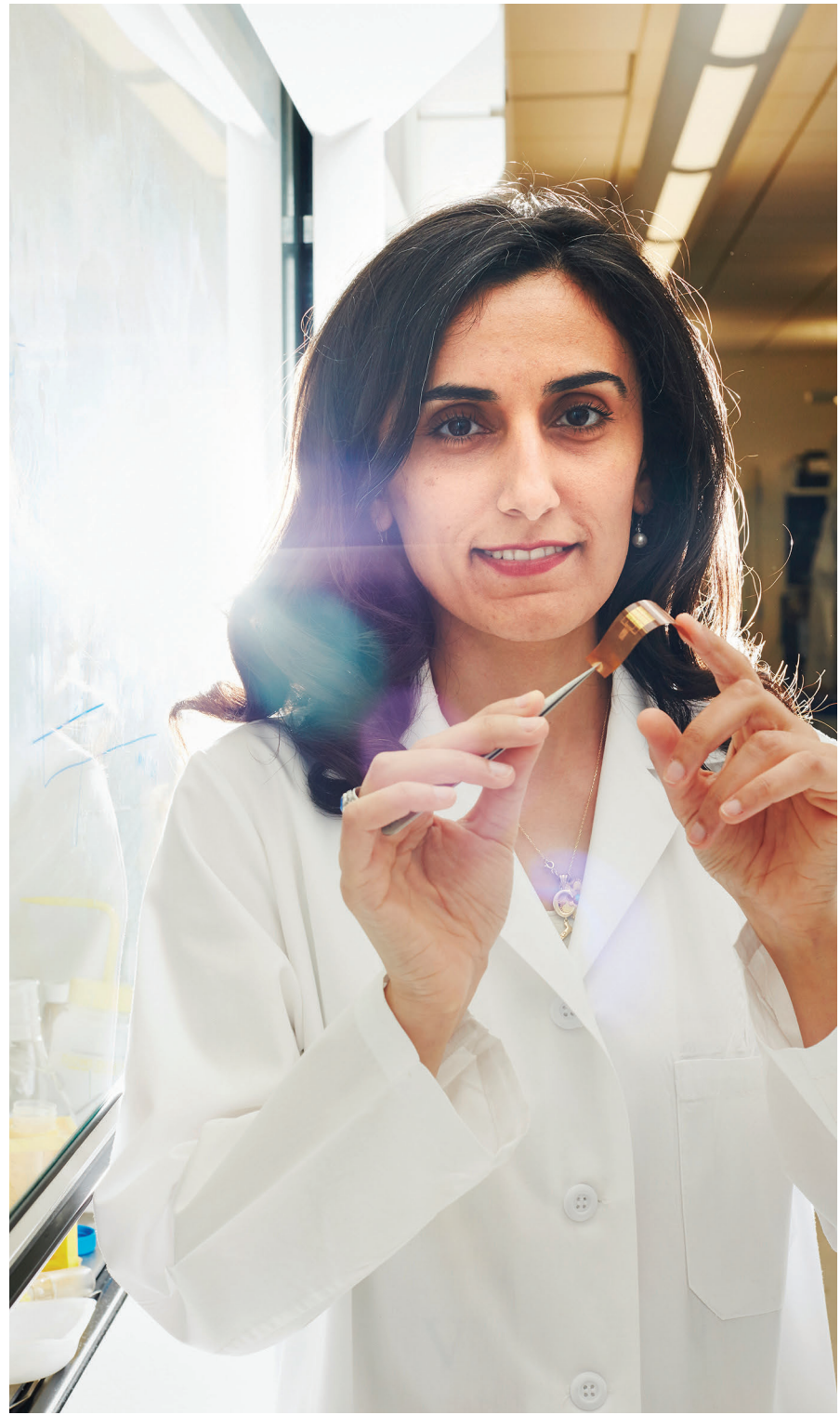
While the flexible energy harvester works by a different mechanism than her skin sensor, both projects fit with the overall goal Dagdeviren is pursuing as a postdoctoral researcher at **Harvard** and **MIT**: creating a new class of biomedical electronics that are far less rigid and clunky than what we use today. *—Julia Sklar*

MAGOZ









At right and in the top two images, Dagdeviren displays flexible, implantable devices that harvest energy from the movement of organs. Third image above: a close-up of the wiring. Fourth image: Dagdeviren's stretchable skin sensor for detecting early signs of cancer.

CHRISTOPHER CHURCHILL

Inventors

Yunji Chen
Improvements in artificial intelligence call out for new hardware.

"The current smartphone is not smart. But if the phone can continuously learn, then it could be."

Yunji Chen, iconoclastic and cosmopolitan, is sporting an untucked flannel shirt and sipping a mango smoothie at an Italian coffee shop in Beijing. He is talking about how he can make deep learning, a hot field of artificial intelligence, far more useful to people.

Once an obscure research branch, deep learning has quickly improved image search, speech recognition, and other aspects of computing (see "Teaching Machines to Understand Us," page 70). Companies such as Google and Baidu are heavily invested in using it to get computers to learn about the world from vast quantities of data without having to be manually taught. However, the technology is resource-intensive: when the Google Brain project trained a computer to recognize a cat face in 2012, it required 16,000 microprocessor cores. That dismays Chen. "The expense and energy consumption is quite high," he says, noting that only large companies can afford it.

The reason is that most processors can quickly repeat basic math functions but need "hundreds of instructions" to perform the more elaborate functions needed in advanced AI techniques, Chen says. So he is designing dedicated deep-learning processors, optimized "to compute the basic blocks of machine learning." In his lab at the **Institute of Computing Technology**, research assistants run a computer program that simulates how precise tweaks in chip blueprints will affect processing speeds. "We are changing the wires, the connections, the circuits," he says. His latest design appears to be hundreds of times faster than today's central processing units, yet it requires only a thousandth as much energy.

As impressive as that may be, Chen, who entered college at age 14 and raced through his PhD in computer science by 24, envisions reducing energy consumption by a factor of 10,000, which could let deep-learning functions work on mobile or wearable devices. "After five or more years," he says, "I think each cell phone can be as powerful as Google Brain." *—Christina Larson*

JAMIE SHOTTON

He gives computers new ways to see the world.

While working at **Microsoft Research** shortly after he earned his PhD in computer vision at the University of Cambridge, Jamie Shotton developed a way for a computer to identify different objects in a moving video. By dividing pixels into segments according to color, the software could separate, for example, a sheep from a field, or a bookshelf from a desk.

This brought Shotton widespread attention, and one evening he received a call asking him to join a secret team working on a new video-game control system for Microsoft. The group hoped to have the system classify individual human body parts in a video stream and then allow people to interact with a game using nothing but their bodies. In the shower one day, Shotton realized that he could segment objects according to their distance from the camera rather than their color.

That led to Kinect, a motion sensor for the Xbox 360 game console that was a monumental development in computer vision and machine learning. It has not represented a sea change in computer interaction, though, perhaps because it requires too much physical effort to use one's body in such a way for a sustained length of time. Shotton remains undeterred. His latest software will debut in HoloLens, Microsoft's forthcoming augmented-reality device. It allows even basic depth-sensing webcams to interpret subtle hand movements. A user can zoom in with a simple pinch of the fingers in space, or enter a password using nothing but hand signals. "There are new and better ways of interacting with computers in the future," he says. *—Simon Parkin*

BENJAMIN TEE

A synthetic sense of touch could help both people and machines.

"As a kid I was always curious about things, and I tended to break things," says Benjamin Tee. "One of the things I broke was my great-grandmother's alarm clock—you know, back then it was a winding alarm clock, it was one of those really old antiques, and she got really upset when I broke it and I couldn't fix it."

The experience only made Tee more curious about how things worked, and now, through innovations in electronic skin and pressure-sensing devices, he is addressing much more complex problems than fixing an alarm clock.

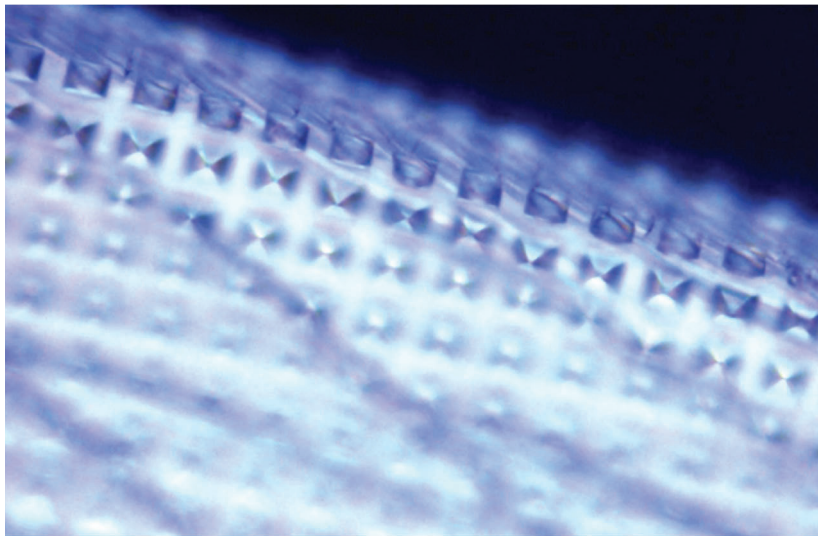
As a PhD student at Stanford, Tee and colleagues built what he calls "a smart bandage." Tape it on your wrist, "and it can detect your pulse on the radial artery near the wrist," he says. "We did it in such a high-resolution manner that we can tell if your arteries are actually healthy."

He also developed a highly pressure-sensitive electronic skin, which could someday coat prosthetic limbs to give them some of the sense of touch that human skin has. "Your brain needs a lot of feedback to do your daily activities, and the skin allows you to do that," Tee explains. "The fact that I'm sitting down and not falling over—a large part is really because I'm getting sensory information from the chair."

Inspired by slicing his finger while making lasagna, Tee has also invented electronic skin that can heal itself multiple times.

Such sensors have other applications: for example, a tiny wireless monitor can be implanted in the skull to measure pressure inside the brain, a technology he has tested in mice. Measuring cranial pressure is extremely important for people who have had brain injuries or are recovering from brain surgery, and doctors usually do it by implanting a catheter that runs through a small hole in the skull.

Today Tee has a Singapore-based startup, **Privi Medical**, that is developing diagnostic and treatment technologies. It should offer him more chances to fix problems, given that health care, he says, is "ripe for disruption." *—Anna Nowogrodzki*



COURTESY OF BENJAMIN TEE

Small pyramids in Tee's electronic skin distort with pressure, altering the electrical charge they hold.

LISA DELUCA

A software engineer makes a habit of going after everyday problems.

With more than 150 patents, Lisa Seacat DeLuca is **IBM**'s most prolific female inventor ever. Her inventions include a way for people on conference calls to get alerts when a certain topic comes up or a certain person starts talking; a system that can guide cell-phone users as they walk and talk so they don't lose service; a necklace that lights up every time a given Twitter hashtag is used; and a locator service in cars that can track items like, say, a wallet that falls under the seat.

"The idea generation isn't the slow part," DeLuca says. "Anyone can come up with ideas very quickly. It's taking the time to write them down and do research to figure out if it's a great idea or how to make it an even better idea—that's really the bottleneck in innovation."

As a child, DeLuca went through Ms. Pac-Man not by playing it but by figuring out the codes that unlocked each level.

Most of that research happens outside the office on nights and weekends. By day, she works on mobile computing and commerce for IBM. Her latest project is an app for retailers that can send

Inventors

shoppers targeted offers based on their location in a store. DeLuca has filed nine patents related to the app and is testing out the necessary Bluetooth beacons in her own home. She also recently bought a 3-D printer that she plans to use for prototyping ideas. First up: a Fitbit key chain for her husband, who always forgets his fitness tracker on his way to work.

—Suzanne Jacobs

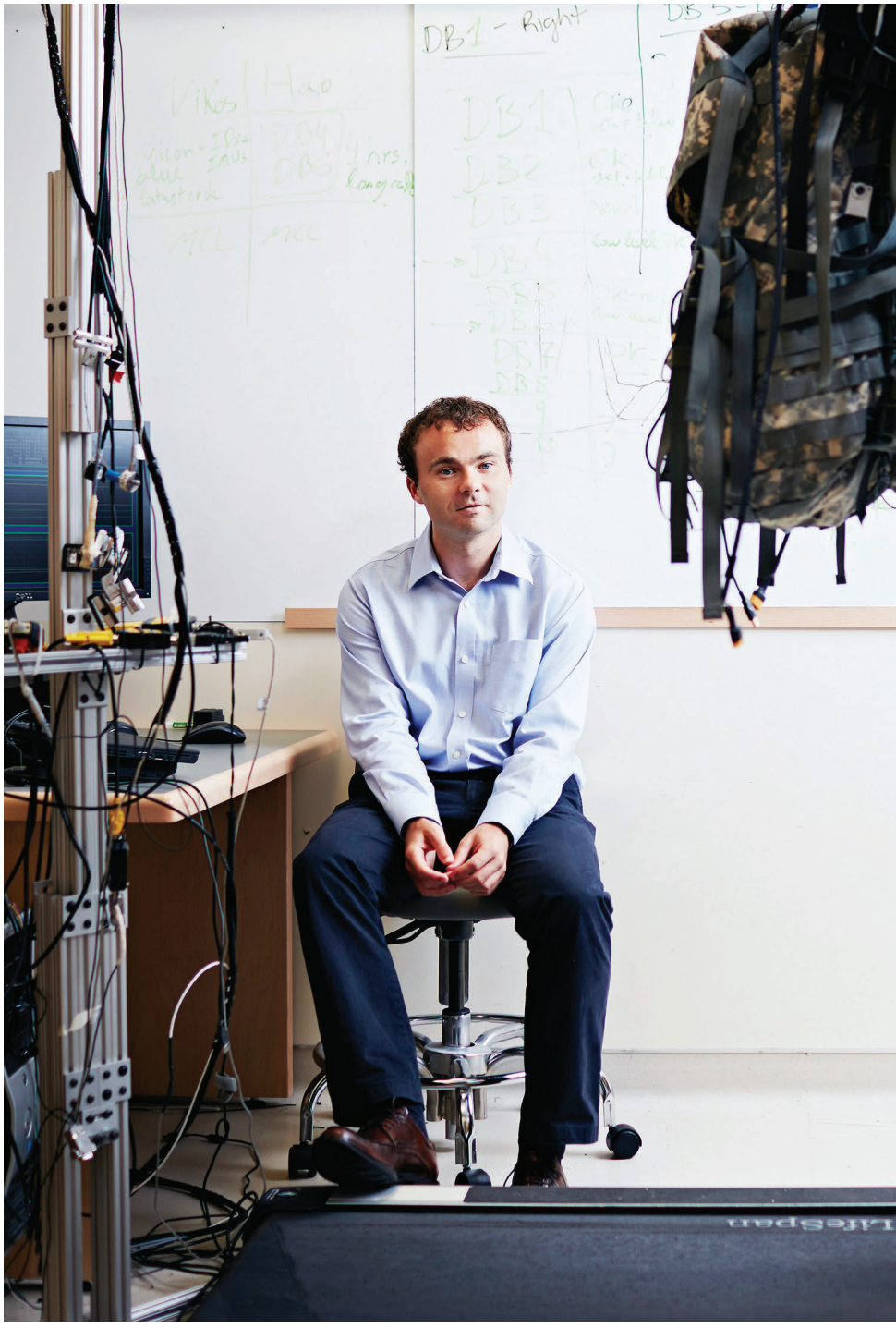
CONOR WALSH

This robotics researcher might have something in just your size.

Most robotics labs don't contain sewing machines. But there's a room full of them in Conor Walsh's lab, along with three full-time textile experts and a wall of fabrics in neat plastic bins. There's a rack that looks as if it belongs in a sporting goods store, with a row of what could be some new kind of running shorts in an array of sizes.

For Walsh, a robot is not necessarily a rigid metal machine. He's working on robots that are soft, lightweight, and flexible so people can wear them to enhance their abilities.

The running shorts are part of an exosuit for the legs. Sensors in the suit mea-



MIGUEL PORLAN; PHOTO BY CHRISTOPHER CHURCHILL

Walsh with a mannequin wearing his robotic exosuit on its legs and a backpack that soldiers use.

sure a person's movement and then tell a motor to pull on cables attached to the fabric in order to assist the muscles at the right moment. The exosuit could support soldiers as they walk, to increase their endurance. Or it could help patients who have trouble walking. "For people whose limbs don't work very well, there's really no good technologies that exist today," says Walsh, a faculty member at **Harvard** and its **Wyss Institute for Biologically Inspired Engineering**. In a video of one trial, a stroke patient walks visibly faster, and with a more symmetrical gait, when the robot is turned on.

Using fabric and cables keeps the exosuit lightweight. But the suit also needs to fit just right, so it can apply forces to the body without restricting movement. "The textile component is probably the most critical," says Walsh. Hence the sewing machines. *—Anna Nowogrodzki*

Travis Deyle

He has built robots that can be powered wirelessly and ones that can bring people medication. Now **Google** has him trying to use technology to improve health care.

Q: At the Google X research lab, you've been part of the team that is building glucose-measuring contact lenses. Now you're working on a different, undisclosed health-care-related project. How do you apply your robotics experience at Google X?

A: Almost every field can benefit from robotics. "Robotics" is really just a nice way of saying "massive multidisciplinary everything," because you have sensing, perception, controls, machine learning, mechanics—everything. Automation. And having that broad exposure lets you plug in to any group, regardless of the domain, and make massive contributions.

Q: What impact do you hope to make?

A: Improving people's lives is the key thing. Health care is one of those things that's been stagnant for a while, and there's a lot of regulatory reasons for that, but there's also just a lot of risk aversion. I think by taking a more agile approach we can actually make giant leaps and bounds.

Q: Why is Google in any kind of position to solve big problems, such as those in health care?

A: It has buy-in from the highest level. Google's founders take risks that no one else will. It reminds me a lot of the amazing things that came out of Bell Labs, like the transistor, which obviously drove entire revolutions in technology. So I think they have the right mind-set to embrace innovation and failure in ways that other organizations just won't. *—Rachel Metz*

Inventors

RICHARD LUNT

Making invisible solar cells for electronic devices requires some exceptional creativity.

Richard Lunt invented solar cells you can see through. They're made of molecules that absorb ultraviolet and infrared light—wavelengths that we can't see—and convert it into electricity while letting visible light through. Applied as a coating on the screen of a phone or smart watch, they generate power so the gadget lasts longer between charges. Some low-power devices with the coating, such as e-readers, might not need to be plugged in at all.

Prototypes of devices with these materials are on display at a company that Lunt cofounded, Ubiquitous Energy (the CEO, Miles Barr, was an Innovator Under 35 in 2014). However, one challenge in developing the technology is that it is complex to manufacture, especially for larger screens. So Lunt is also trying a second approach.

Lunt, a materials scientist based at **Michigan State University**, has concocted a combination of see-through materials that convert ultraviolet and infrared light to wavelengths that are then directed to photovoltaic cells at the edges of the screens. Because this design is simpler than the original approach of putting transparent solar cells directly on the surface of a screen, it could be cheaper to manufacture, especially for bigger devices.

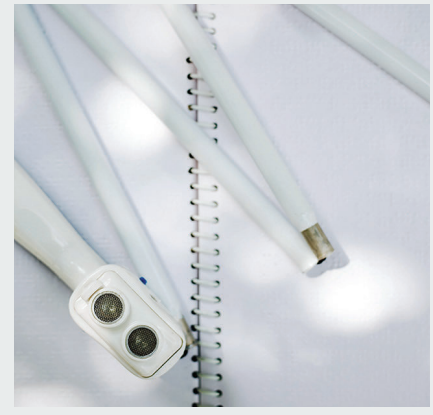
The technology could boost conventional photovoltaic designs, too. If included as a coating on a standard solar panel, Lunt says, the new materials could increase the panel's power output by converting more of the sun's energy to electricity. *—David Talbot*

Rohan Paul

To create an affordable obstacle detection system for blind people, this **MIT** postdoc began by simply asking them what they needed.

These ultrasonic sensors detect obstacles.

The device vibrates in patterns that indicate the distance to obstacles.



The full system includes a foldable cane for easy storage. It can also be mounted on a traditional cane.

CHRISTOPHER CHURCHILL

"In 2005, I was at the Indian Institute of Technology in Delhi as an undergraduate. As part of a course intended to design solutions for real-life challenges, we visited the National Association for the Blind in Delhi. We heard stories of how people with blindness get hurt when out walking—abruptly hitting open windows, tree branches, or vehicles. It creates so much fear that they are reluctant to step out without assistance.

"We envisioned a sensing system on canes. By the end of the first year we had a basic prototype using ultrasonic ranging for detection and vibrations for feedback. You could see the users smile once they detected an obstruction; many refused to give back the prototypes!

"We involved the users from the very beginning. They insisted that the device has to be small; if it falls it should not break; and it should allow any gripping or holding style. It has to detect everything, from signboards, people, parked cycles, or even cattle blocking the path—and also respond to obstacles approaching fast.

"Women told us they wanted a device to be small enough so the cane can fold and fit into their purse. And they debated about color. Why? Because they would show it to someone else and say: 'Am I looking smart with this?' Men wanted to know if it will prevent touching or colliding with people; they told of women turning around and slapping them after such unintentional accidents. They don't want to say, 'Oh ... excuse me, I didn't see.' It is about dignity as well as everyday safety. We engineers at times overlook the human side of a technology like this.

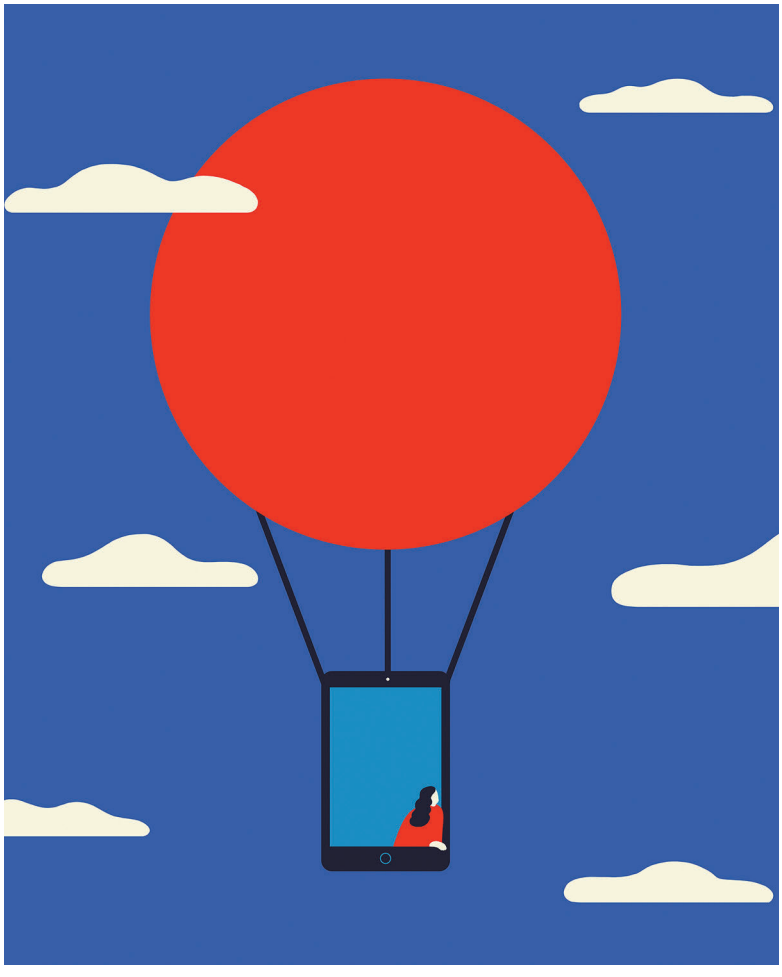
"We ended up with a sleek handle-shaped attachment that fits on the traditional white cane. When we tested it in 2012 we saw users had 95 percent fewer collisions. We released it as a product in early 2014. The SmartCane costs only about $50 and is already in the hands of about 10,000 people. Our aim is to help one million or more worldwide.

"It is a 'people's product'—a humble tribute to the Mahatma, who inspired innovators to harness science and technology for the masses."

—as told to David Talbot

Entrepreneurs

They see technologies as sparks of opportunity.



JINI KIM

A stint helping the government altered her view of her health-care business.

The phone call that changed Jini Kim's life came at 2 A.M. in November 2013. The White House needed the former Google product manager's help with Healthcare.gov, which had been meant to help people buy health insurance but was riddled with embarrassing glitches. She hopped on a plane that day and worked marathon hours to fix the site, giving up Thanksgiving, Christmas, and her birthday. By the time she left, six months later, the site had enrolled eight million people in insurance plans—and Kim had gained insight that would be crucial for her own health-care analytics company, **NunaHealth**.

Before her five-plus years at Google, Kim investigated mental institutions as an intern in the U.S. Department of Justice.

Founded in 2010, Nuna helps companies shape their health-insurance benefits and wellness programs. It analyzes anonymized data about employees' behavior to determine the answers to questions such as "Are there differences in how people in certain demographic groups seek health care?" or "Can more generous health insurance help improve the productivity of someone with a seriously ill family member?"

Before she bailed out Healthcare.gov, Kim viewed the government the way many people in Silicon Valley do: as a hindrance to innovation. Accordingly, Nuna originally sold its services only to corporations. But during her stint working for the Obama administration, she saw the enormous potential the government had to effect change. "You can touch millions of

MAGOZ

people so easily," says Kim, recalling a day at a Healthcare.gov call center when she overheard desperate people crying because they were unable to sign up for insurance.

Upon her return to San Francisco, Kim expanded Nuna so that it now also works with local, state, and national governments. For example, the company helps the Centers for Medicare and Medicaid Services find patterns in their vast amounts of data.

For Kim, reforming health care is not a theoretical issue. Her 33-year-old brother, Kimong, has severe autism. She has been involved in his care since she was nine years old and had to sign him up for Medicaid on behalf of her immigrant parents. She still lives at home to help out. Nuna's meeting rooms are named after Kimong's favorite *Sesame Street* characters, and she brings him to work regularly to give her parents a break. The name "Nuna" comes from the Korean word for "big sister," one of three words he knows.

—Yukari Iwatani Kane

Patrick Collison

He and his brother started **Stripe** to make money flow easily online.

"I grew up in very rural Ireland. The Internet was a connection to the greater world. It was very clear just how potent a force the Internet was and could be. While my brother John and I were tinkering with some new apps in Ireland and then in Boston and Silicon Valley, we experienced firsthand the difficulty of accepting online payments. We were just baffled at how convoluted and awkward the process appeared to be. The ecosystem seemed designed to reduce the number of Internet businesses.

"The same way Google exists as a foundational component of the Internet around information retrieval, it felt like there should be a developer-focused, instant-setup payment platform. Many people in financial services told us it couldn't work.

"Stripe now processes billions of dollars a year for thousands of businesses, from startups to publicly traded companies. There's a ton of database and distributed-system work that has to be done to make that experience possible. We have a 10-person machine-learning team that works on compliance, risk, fraud, identity verification, all of those things behind the scenes.

"Making it so easy to participate in the online economy has a far larger effect than one might imagine. We're enabling new business models, like crowdfunding. And mobile marketplaces, like Lyft, Postmates, and Instacart. That enables more people in society to take advantage of these services. My youngest brother is disabled, and for him it's not just a convenience. He can now do grocery shopping in a way that he could not before." *—as told to Robert D. Hof*

RIKKY MULLER

Hardware that buzzes the brain at the right moments could help treat debilitating mental disorders.

One of the most audacious projects funded last year under the Obama administration's BRAIN initiative aims to intervene in mental disorders using an electrical brain interface. The plan is to develop a system that both senses and modulates abnormal electrical activity, in hope of helping patients with conditions ranging from severe anxiety to post-traumatic stress disorder. Rikky Muller, an Israeli-born entrepreneur and the cofounder of **Cortera Neurotechnologies**, is designing the implantable hardware intended to interact directly with the brain.

Muller has long been interested in brain interfaces with clinical potential. After training as an electrical engineer and then designing chips for digital cameras, she gravitated toward neuroscience. In graduate school at Berkeley, she worked on neural implants that might decode human thought to control robotic prostheses. She also built a wireless device that could interpret brain signals in detail while resting on the surface of the cortex, rather than deeper in the brain. That work led to the founding of Cortera, in 2013, during the final year of her PhD studies. "We thought it could change patients' lives," she says.

Devices that record electrical activity directly from the surface of the brain—like Cortera's founding work—are already used clinically to map the cortex during surgery and to pinpoint the location of seizures. In theory, these devices could also monitor severe neurological or psychiatric conditions on an ongoing basis. Muller is cagey, however, when it comes to Cortera's plans in the growing neuromodulation market. "We do have a specific application in mind," she says, "but we are not disclosing what it is." *—Amanda Schaffer*

Entrepreneurs

MELONEE WISE

Affordable robots for the warehouse and beyond.

Melonee Wise imagines that all homes will have autonomous robots—something like *The Jetsons*' Rosie the robot maid, minus the apron and Brooklyn accent. Just one problem: Wise, chief executive of the year-old startup **Fetch Robotics**, thinks it won't happen in her lifetime, because the challenges in hardware and software are too big. "I'm probably one of the most pessimistic roboticists you'll ever meet," she admits.

Nonetheless, Wise still thinks smaller and more powerful computers, affordable sensors, more adept machine vision, and better artificial intelligence are coming together to make robots capable of a wide range of tasks—if not yet all in a single machine. That's why Fetch Robotics is going after one promising area: warehouses and e-commerce fulfillment centers, which are plagued with high turnover, injuries, employee theft, and a chronic shortage of workers, who, of course, also have a biological need to sleep.

Although dedicated robots are common in giant distribution centers (see "Inside Amazon," page 62), Wise thinks there's a bigger market for more flexible "mobile manipulation" robots that can help smaller companies ease into automation. In a simulated warehouse set up in a corner of Fetch's San Jose headquarters, a knee-high, cylindrical rolling robot called Freight smoothly follows Wise like a very attentive dog as she picks up boxes of crackers and cereal from shelves. She drops them in a plastic crate atop the robot, and when she's done with the fake order, it zips off to a mock shipping area.

Another robot, Fetch, is intended not to aid but to replace warehouse workers. It has one jointed arm with a gripper on the end, along with a "head" that uses a depth camera similar to a Microsoft Kinect game controller, so it can identify and pluck items from a shelf and place them in Freight's crate. Both robots are taught to navigate by leading them around the warehouse to create a map. They're even trained to recognize people's legs, so they can follow particular individuals. Unlike some robots that navigate using radio beacons or bar codes on the floor, Fetch's robots use 3-D laser scanners to get around and avoid obstacles, expected or otherwise.

Wise spent more than five years at Willow Garage, a seminal robotics incubator that has spawned a half-dozen startups.

Wise won't disclose the exact price of Fetch robots, but she says they will be in the tens of thousands—much less than the cost of an employee. The company has sold some of its initial run of 40 robots to unnamed pilot customers, with plans for a much larger run if the automated workers can do the job. *—Robert D. Hof*

Ben Rubin

The cofounder of a live-streaming video app explains what makes it tick.

"Three things: simple, rewarding, and not creepy."

Ben Rubin is talking about the key qualities of **Meerkat**, an app that helped fuel a live-streaming craze this year. Type in a subject, press a button to start filming with your smartphone camera, and Meerkat sends out a tweet with a link that your friends can click to watch—and comment on if they want. That's all it had to be, he says: "The medium is new, and if you make a complicated product in a medium that already makes people uncomfortable, you end up with zero adopters."

One thing Rubin couldn't control, however: after Meerkat got popular, Twitter began offering a similar app, Periscope, and cut off Meerkat's access to its network. That made it harder for new users to find friends who also use Meerkat. The company has since let users connect Meerkat to their Facebook profiles.

Rubin envisions live-streaming eventually giving rise to a new form of entertainment: "an ongoing live show that is taking place in real time and involves the audience and everyone. Something where you're no longer the couch potato; you're part of the script." *—Rachel Metz*

To keep costs low, Wise's robots use only 500 unique parts. Top right: The Freight robot moves a crate. Bottom right: Fetch waits at a row of shelves.

Dena Marrinucci Her startup bets it can track cancer from an early stage, without any biopsies.

WINNI WINTERMEYER

Problem:
Tumor cells that metastasize through the blood are generally very difficult to detect until they have spread to the point of being deadly.

Solution:
Dena Marrinucci cofounded **Epic Sciences** in 2008 to commercialize a cell detection and analysis technology that she developed to find cancer earlier. It can find and profile nearly all the tumor cells in two tablespoons of blood taken from a patient. On average, a sample that size has 50 billion red blood cells, 50 million white blood cells, and only a few circulating tumor cells. "You're basically looking for needles in a haystack," says Marrinucci.

Other technologies miss some circulating tumor cells because they are scanning for only one biological marker or are filtering cells by size. Epic says it finds more because it detects not only genomic abnormalities but also other biological markers, such as protein expression in cells. That should be useful in tracking the progress of a patient's cancer over time, so that treatments can be adjusted as the disease evolves. Twenty-six pharmaceutical companies are using Epic's technology in clinical trials of cancer drugs.

Marrinucci had just begun graduate school at the Scripps Research Institute in San Diego in 2004 when her grandmother was diagnosed with advanced melanoma. Less than a year earlier, however, doctors had given her grandmother an all-clear after a PET scan. "By the time you see cancer cells on a PET or CT scan, there are thousands of them," she says. "And that's what we're trying to change." *—Eilene Zimmermann*

Entrepreneurs

"Images are universal," Systrom says. "They transcend language and cultural barriers."

WINNI WINTERMEYER

KEVIN SYSTROM

Instagram's cofounder maintains his sharp focus.

Kevin Systrom started **Instagram** in 2010, when he was 26, with a guy he'd befriended in a San Francisco coffee bar. Eighteen months later, when the company was just 13 people and still without a business plan, Mark Zuckerberg came calling with an offer of $300 million in cash and $700 million in Facebook's pre-IPO stock. Systrom said yes only after he persuaded Zuckerberg to keep the Instagram brand alive and to let him and cofounder Mike Krieger run it.

Three years later, it's clear that the creation of Instagram was remarkably well timed and well executed. The service is like Twitter, but with pictures and videos primary rather than text. It works because people like to tell stories with pictures: it's easy, and it has impact across languages and cultures. Instagram has more than 300 million users, who post more than 70 million photos and videos every day.

One big question still faces Systrom, though: can he turn all this attention into a real business? He started rolling out an advertising program last fall and remains coy about how it's doing. Systrom says he just has to find a way to present the ads without upsetting his users, the vast majority of whom are younger than 30.

Systrom himself is something of a model for an emerging kind of high-tech entrepreneur, at the intersection of technology and the liberal arts. He's a jock, having been captain of his high school lacrosse team. He's also artistic, having effectively minored in photography while getting an engineering and management degree at Stanford. He knows the corporate world: he's on the board of Walmart. And he's an extrovert, as comfortable with runway models in New York and movie stars in Hollywood as he is with coders in Silicon Valley. As mobile applications and social networking permeate more of our economy, people who understand how these technologies make the physical world more interesting or productive will become as important as the hard-core engineers.

—Fred Vogelstein

Visionaries

These people are showing how technologies will give us new ways of doing things.

MAGOZ

ILYA SUTSKEVER

Why one form of machine learning will be particularly powerful.

Artificial-intelligence researchers are focusing on a method called deep learning, which gets computers to recognize patterns in data on their own (see "Teaching Machines to Understand Us," page 70). One person who demonstrated its potential is Ilya Sutskever, who trained under a deep-learning pioneer at the University of Toronto and used the technique to win an image-recognition challenge in 2012. He is now a key member of the **Google Brain research team**. I asked him why deep learning could mimic human vision and solve many other challenges.

"When you look at something, you know what it is in a fraction of a second," he says. "And yet our neurons operate extremely slowly. That means your brain must only need a modest number of parallel computations. An artificial neural network is nothing but a sequence of very parallel, simple computations.

"We started a company to keep applying this approach to different problems and expand its range of capabilities. Soon,

Sutskever says he was interested in AI when he began college but "it seemed impossible, so I studied math instead."

we joined Google. I've shown that the same philosophy that worked for image recognition can also achieve really good results for translation between languages. It should beat existing translation technology by a good margin. I think you will see deep learning make a lot of progress in many areas. It doesn't make any assumptions about the nature of problems, so it is applicable to many things." *—Tom Simonite*

Visionaries

The most recent SpaceX launch was an ill-fated mission in June.

LARS BLACKMORE

Would space travel flourish if we could reuse the rockets?

Sixty years after *Sputnik* blasted into space, escaping our atmosphere remains absurdly expensive. Lars Blackmore, an engineer at **SpaceX**, is working on changing that with rockets that could be flown back to Earth in reverse.

As things stand, every time a space rocket takes off and releases its payload, it breaks up and falls into the ocean. "It's basically like flying a 747 across the country and then, instead of refueling it, throwing it away," says Blackmore, a soft-spoken Brit who leads a team at SpaceX that's developing the onboard software necessary for a rocket to come down gently in an upright position onto a platform in the ocean.

SpaceX has come agonizingly close to sticking a rocket landing several times, but it didn't get a chance to try again in its most recent flight, when the Falcon 9 rocket exploded during takeoff.

Landing a rocket backwards is an insane trick. The descent is extraordinarily unpredictable, and rockets aren't meant to travel in reverse, so it requires extremely fine control over the boosters and guidance fins. Blackmore has devised algorithms to enable a rocket's onboard computer to deal with this chaotic situation while safely controlling the craft's fall.

If the feat can be perfected, it would change the economics of space travel entirely. Fuel accounts for less than half of 1 percent of the cost of a rocket launch, so refurbishing a rocket would make the next launch considerably cheaper. How much cheaper would depend on how well the booster could be reconditioned following the extreme stress of takeoff.

Blackmore grew up dreaming of working at NASA Mission Control. After a PhD at MIT, he joined NASA's Jet Propulsion Lab, where he worked on precision landing systems and a climate probe called SMAP. He went to SpaceX in 2011. "I'd heard that Elon [Musk] had these dreams of making reusable rockets," Blackmore says. "And since I was working on precision landing for Mars, I thought I would be the right guy to do that."

Would he want to go back to NASA someday? "When you hear about the Apollo program in its heyday, it was a bunch of young kids, and no one told them what they could do," he says. "That is exactly what I've found at SpaceX." —*Will Knight*

Cigall Kadoch A major vulnerability of certain kinds of cancer is becoming clear.

Problem:
The exact biochemical mechanisms involved in many kinds of cancer remain unknown.

Solution:
While completing her PhD at Stanford, Cigall Kadoch discovered a link between a genome regulator in cells called the BAF protein complex and a rare cancer called synovial sarcoma. She and colleagues later showed that mutations of BAF are involved in at least 20 percent of human cancers, opening the door for research on drugs that target mutated BAFs.

BAF's job in the cell is to open and close DNA to allow the right genes to be expressed at the right time. When mutated, it can "activate sites that it shouldn't"—including genes that drive cancer, says Kadoch, who has appointments at **Harvard Medical School** and the **Broad Institute of Harvard and MIT**.

She learned this by focusing on one particular subunit of BAF. This piece of the protein has a deformed tail in 100 percent of patients with synovial sarcoma. When Kadoch put the deformed subunit into normal cells, she detected "blazing cancer," she says. "That little tail is entirely responsible for this cancer."

The good news is that this is reversible. If she added enough normal pieces of the subunit to cells in a petri dish, it replaced the mutated form, killing the cancerous cells on the spot. —*Anna Nowogrodzki*

BOB O'CONNOR

Register today:
technologyreview.com
/emtech
MIT Technology Review
subscribers save 15%.
Use promotional code
TRSub at registration.

A PLACE OF INSIGHT

MIT Technology Review

EmTech

November 2–4, 2015

MIT Media Lab, Cambridge, MA

technologyreview.com/emtech

WE'LL EXAMINE: Augmented Knowledge, Better Living Through Data, Infinite Energy, Rethinking Urban Infrastructure, Robots Among Us

Featured speakers include:

Leslie Dewan
Cofounder and Chief Science Officer, Transatomic Power
Rethinking Nuclear Power

Julia Greer
Professor of Materials Science and Mechanics, California Institute of Technology
10 Breakthrough Technologies 2015: Nano-Architecture

Eric Horvitz
Distinguished Scientist and Director, Microsoft Research
The Promise of AI

Steve Jurvetson
Partner, DFJ
Investing in Big Ideas

Christopher Soghoian
Principal Technologist, ACLU
Privacy and Security in the Digital Age

Event Partners

ANALOG DEVICES · Ford | SYNC · LEMELSON-MIT · THE HARTFORD · MIT PROFESSIONAL EDUCATION · MITSloan Executive Education

Visionaries

ZAKIR DURUMERIC

A computer scientist sees a way to improve online security.

"It's absolutely astounding what people attach to the Internet," Zakir Durumeric says. He would know, because he invented a way to probe every computer online in just minutes. "We have found everything from ATM machines and bank safes to industrial control systems for power plants," he says. "It's kind of scary."

A bank safe! Why would someone put that online? So someone in the bank can operate it from home?

"Yes. You sit there and you wonder: who on earth thought this was a good idea?"

Bad computer security practices like that can be mitigated far more readily with the ZMap scanning system Durumeric developed. It determines not only which machines are online at any given moment, but also whether they have security flaws that should be fixed before miscreants exploit them. It finds everything from obvious software bugs to subtle problems like the ones that can be caused if an IT administrator fails to properly implement an arcane aspect of a cryptography standard.

Pinging all four billion devices on the Internet took weeks until Durumeric, who is pursuing a PhD at the **University of Michigan**, came up with a process that now takes about five minutes. He has used it to quickly inform website administrators about their vulnerability to catastrophic flaws such as the Heartbleed bug in 2014, and he hopes other security researchers will routinely do the same when they find weaknesses. "There's always been this period where a vulnerability is [found] and then it takes weeks, months, or years for administrators to patch their servers," he says. "We have an opportunity to change that." *—Brian Bergstein*

Adam Coates

Artificial intelligence could make the Internet more useful to the millions of people coming online for the first time.

Q: You invented ways to put more computing power behind deep learning. Now you lead a lab in Silicon Valley for the Chinese search company **Baidu**. Why did it need a lab there?
A: They spin up new projects very fast. It's partly driven by the dynamism in China—tech companies have to go quickly from having nothing to having state-of-the-art something. My lab's mission is to create technology that will have an impact on at least 100 million people; it is intended to move rapidly, like a startup. We're recruiting AI researchers and many people in Silicon Valley who have amazing skills from working on products and haven't thought they could use that to make progress on artificial intelligence.

Q: What is the lab working on?
A: The first technology that we are focusing on is speech recognition. Touch screens on phones are fine for some things but really awful for others, and there are all kinds of other devices that are crying out for better interfaces. People don't use speech today because it doesn't work well enough. Our goal is to get it to a level where it's as easy to talk to your devices as it is to talk to the person next to you. In December we hit our first milestone with DeepSpeech, a speech engine we built quickly from scratch using deep learning. When there's a lot of background noise it's dramatically better.

Q: Why would that have an impact on 100 million people?
A: In rapidly developing economies like in China, there are many people who will be connecting to the Internet for the first time through a mobile phone. Having a way to interact with a device or get the answer to a question as easily as talking to a person is even more powerful to them. I think of Baidu's customers as having a greater need for artificial intelligence than myself. *—Tom Simonite*

MIGUEL PORLAN

A PLACE OF INSPIRATION

MIT Technology Review **EmTech**

November 2–4, 2015

MIT Media Lab, Cambridge, MA

technologyreview.com/emtech

EmTech MIT is an opportunity to discover future trends and begin to understand the technologies that will drive the global economy. It's where technology, business, and culture converge, and where you gain access to the world's most innovative people and companies. At the 15th annual EmTech MIT, we will introduce you to the 2015 Innovators Under 35.

Past honorees include:

Ayah Bdeir
Founder and CEO, littleBits
2014 Innovator Under 35

Rand Hindi
Founder and CEO, Snips
2014 Innovator Under 35

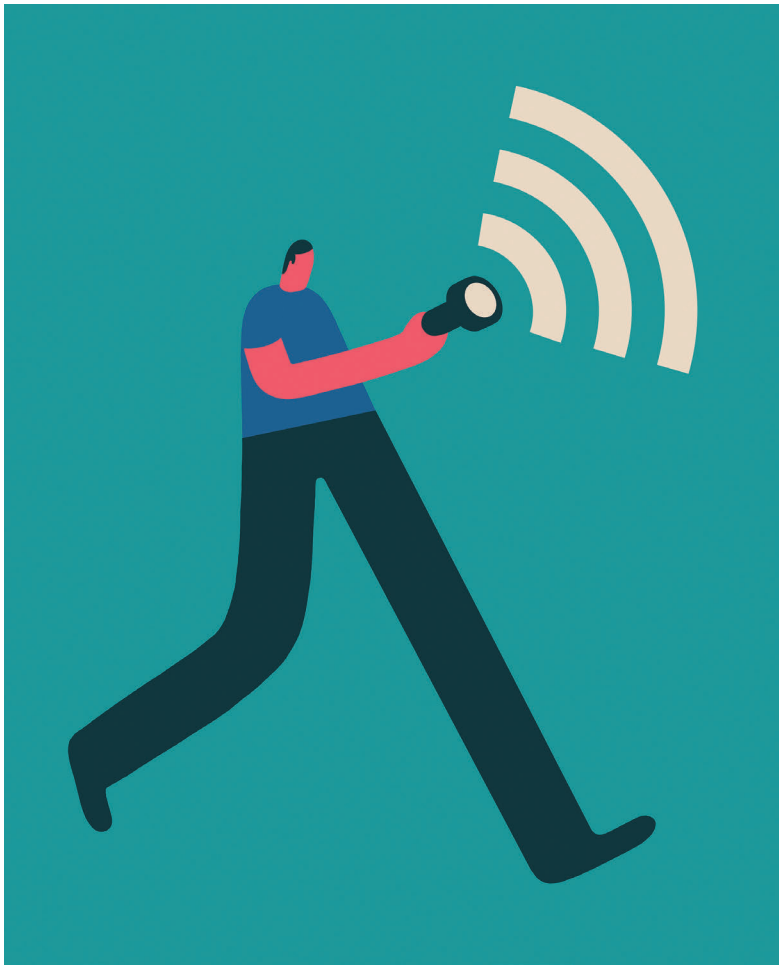
Quoc Le
Research Scientist,
Google Brain
2014 Innovator Under 35

Aaron Levie
Cofounder and CEO, Box
2014 Innovator Under 35

Julie Shah
Assistant Professor, MIT
2014 Innovator Under 35

Pioneers

Extending our scientific knowledge and paving the way for future technologies.



ELIZABETH MORMINO

A telltale protein seen in people's brains before they have Alzheimer's could offer a clue about possible treatments.

Elizabeth Mormino knows it's too late to save her grandfather, whose Alzheimer's disease was diagnosed a few years ago. "It's really hard to see a familiar face go through this, knowing that there's really no drugs that work right now," she says. But her work may help future patients by showing an intriguing new path to treating the disease.

Mormino has figured out a way to combine two imaging technologies to detect the protein beta-amyloid, which is found in patients with Alzheimer's, and has used them to look at the brains of people with no signs of cognitive decline. Although researchers have already been using one of the imaging technologies, called PIB-PET, to see beta-amyloid in the brains of living patients for a few years, Mormino is able to identify brain regions more accurately by combining PIB-PET and MRI data.

"I feel like we're taking snapshots of people's brains," she says. "It feels very personal and intimate."

The most surprising insight from her work is that some outwardly normal people are "walking around with a head full of amyloid, and oftentimes as much amyloid as somebody who actually has clinical Alzheimer's disease," she says.

How could this be? One hypothesis is that amyloid causes neurons to die, which then causes the clinical symptoms of Alzheimer's. So by the time patients have Alzheimer's, anti-amyloid treatment is too late—the protein has already damaged too many brain cells. (Indeed, anti-amyloid drugs have not proved effective at treating Alzheimer's.) But some of

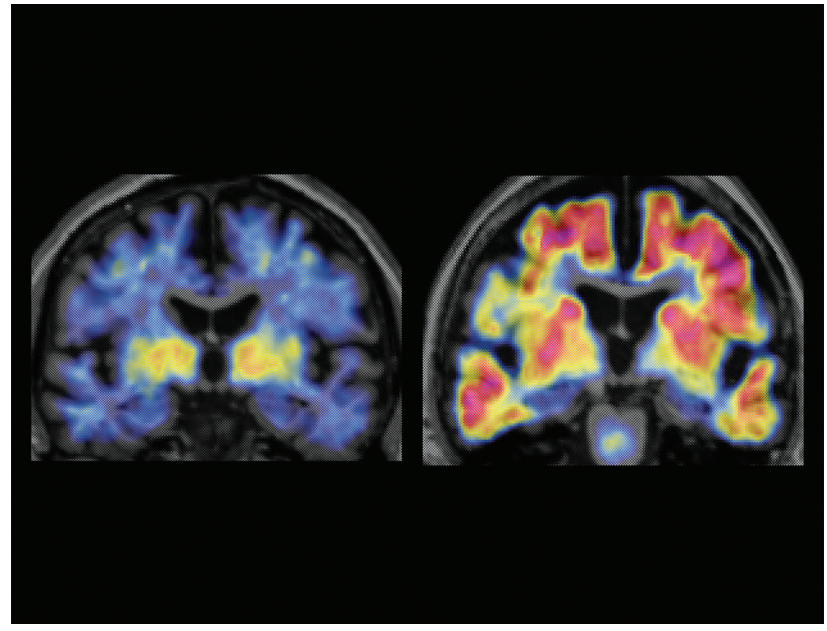
MAGOZ

her healthy patients could have protective factors, whether in their genes or in their lifestyle, that allow them to tolerate high amyloid levels without developing Alzheimer's.

Understanding such protective factors might "offer some insights into successful aging or the ability to remain resilient," says Mormino. And there is a chance it could help specifically with Alzheimer's prevention. To that end, researchers at the University of California, San Diego, and **Massachusetts General Hospital**, where Mormino is an assistant in neuroscience, have started clinical trials in which people who have high amyloid levels but no Alzheimer's symptoms are getting anti-amyloid infusions to see if that staves off the disease.

The hope is that eventually Alzheimer's could be prevented by regularly checking and treating amyloid levels, much the way heart attacks are averted by monitoring cholesterol.

—Anna Nowogrodzki



These brain scans intrigue Mormino because both come from healthy patients, and yet the one on the right is riddled with amyloid, seen in red.

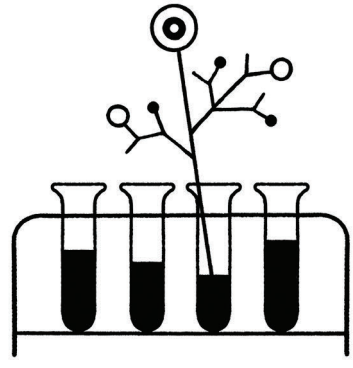
MIGUEL PORLAN; BRAIN SCANS COURTESY OF ELIZABETH MORMINO

JUN GE

Why we might use tiny flowers, trees, and spindles to create the pharmaceuticals of the future.

Manufacturing pharmaceuticals is typically a messy business. Catalyzing the necessary chemical reactions often requires toxic solvents and large amounts of energy. Jun Ge hopes to clean up the process substantially by instead harnessing enzymes, nature's catalysts, to do the work.

Lots of people have had that idea. The challenge is that enzymes tend not to hold up well in industrial processes, and protecting them by attaching them to other materials greatly lessens their activity level. But Ge, a slender and soft-spoken chemical engineer at China's elite **Tsinghua University**, had an insight a few years ago. While working as a postdoc at Stanford, he had a hunch that adding copper ions to a solution containing a certain enzyme could help activate and stabilize it. What he didn't expect to find were the wondrously strange structures that soon precipitated at the bottom of his test tube: "very beautiful structures, like flowers made of protein and crystal." Significantly, the enzymes held in this extraordinary "nano-flower" shape are stable and seven times more active than when they float freely in a solution. The findings made the cover of *Nature Nanotechnology* in 2012.



Ge, who grew up in a "small, beautiful city" in Jiangsu Province, wants to help address China's environmental problems.

Today Ge is studying a range of enzyme nanostructures—which he dubs "nano-trees" and "nano-spindles"—and exploring whether they could be used in everything from the production of a cancer drug to a next-generation glucose strip for diagnosing diabetes. *—Christina Larson*

Pioneers

AASWATH RAMAN

Your next air-conditioning system might save energy by beaming heat into outer space.

Aaswath Raman holds a thin, silvery disc. It looks like a very clean mirror, but it's hardly ordinary: it gets colder under direct sunlight and stays about 5 °C cooler than the surrounding air.

Raman is a practical person with a gentle personality; his button-down shirt and flip-flops blend in on the campus of **Stanford**, where he is a postdoctoral researcher. This mirror, he calmly explains, has a coating that sends heat into the vastness of outer space—which could make it ideal for air-conditioning and refrigeration systems that would require very little or no electricity.

Raman has $3 million in funding from the Advanced Research Projects Agency for Energy to develop the technology.

The cooling material takes advantage of a fascinating phenomenon. Objects are always cooling down by radiating heat—this is why dew forms on blades of grass at night. Some of the radiation occurs at frequencies that send the energy right through Earth's atmosphere and into space, allowing the object's temperature to drop below that of the surrounding air.

During the day, the sun's heat usually overwhelms the cooling effect. But while reading through old papers on the subject from the 1960s, Raman thought of a way around that. He applied his knowledge of nanoscale manufacturing techniques that didn't exist decades ago to make something with optimum levels of thermal radiation and solar reflection. It is a multilayered film of hafnium dioxide, silica, and other materials deposited at carefully controlled thicknesses. It can be made over large areas using the same manufacturing techniques that are used to coat windows.

Coating the roof of a small structure with some of his material would wick heat away and keep the inside cool without electricity, as long as the roof wasn't insulated. Since most buildings in developed areas have insulated roofs, Raman is working on integrating the material into existing air-conditioning infrastructure. He has a prototype on the roof of Stanford's Packard Electrical Engineering Building. It is made up of a sheet of the passive cooling material about a square meter in area, mounted in a custom-machined plexiglass box patterned with water channels. In a finished system, the water would circulate through the building air-conditioning system, then go into the cooler box to chill and back into the building system. However, he still needs to demonstrate that his prototype can chill a substantial volume of water.

He has already partnered with a manufacturer that can produce large sheets of the cooling material for further development. He jokes that many researchers in his branch of physics tend to stay in their labs all day and "don't like to go outside." But he adds: "If you just go outside, there's opportunity." *—Katherine Bourzac*

Zhen Gu Diabetics are tired of sticking themselves with needles. Someday they may not have to.

Problem:

People with diabetes must monitor their blood sugar and inject themselves with insulin several times a day. Even those with insulin pumps risk complications from injecting too much or too little insulin.

Solution:

Zhen Gu, a researcher at the **University of North Carolina**, whose grandmother died from diabetes complications, is developing insulin delivery mechanisms that could be better. The most recent one is a fingernail-size patch covered in more than 100 microneedles. When you put the patch on your skin, you feel momentary pinpricks as the needles poke into your blood vessels. The needles are full of tiny sacs containing insulin and an enzyme. The sac is just permeable enough to allow glucose inside, where the enzyme converts it to an acid that—when blood sugar is too high—makes the sac open and release the insulin. The sacs fall apart at different rates, so the insulin is released over hours rather than in one burst.

When Gu tested the patch on five mice, it controlled their blood sugar for nine hours, although it takes half an hour to work, and people without diabetes naturally regulate their blood sugar much faster than that. Now he has begun testing the patch on pigs, whose thin skin is more similar to humans'. Eventually, Gu hopes, people with diabetes could slap on a patch every two or three days to reliably and precisely control blood sugar without much pain or effort. *—Anna Nowogrodzki*

Polina Anikeeva

A creative scientist sees new ways to record and stimulate brain activity.

Anikeeva says medical devices should be far more sophisticated.

KEN RICHARDSON

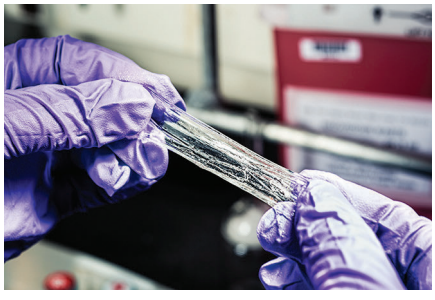
"For my PhD at **MIT**, I worked on quantum-dot LEDs, and having zero biological experience, I chose to spend two years in Karl Deisseroth's neuroscience lab at Stanford. When I saw that they were developing methods to control the brain optically and investigate brain function, I was really blown away. [But] the tools we were using were too large and too bulky, and didn't have enough capability. Since my background was nano-optoelectronics and nanofabrication, I felt that we should be able to do better. That became the foundation of my lab [at MIT].

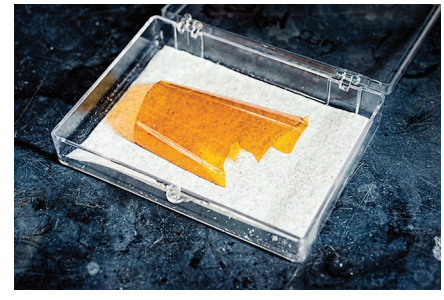
"The lab is divided into two main directions. One is using fiber fabrication to create neural probes that have multiple functions. The other is to figure out if we can interact with the nervous system in an essentially wireless and noninvasive way.

"Ultimately, you want to figure out how specific patterns of neural activity correspond to specific behaviors. What we're trying to do is push the resolution of our recording and stimulation capability, which will allow us to decipher those neural circuits. If you're trying to, say, restore function after spinal-cord injury, if we were able to record signals from both sides [of the injury] and convert them into patterns of stimulation, we would be able to start building a synthetic bridge across that connection. Right now, we would love to work with people and get this technology into as many labs as we can."

—as told to Courtney Humphries

Pioneers





Garcia at IBM's Almaden research center in San Jose, California. Left: a material she created that solidifies under ultraviolet light but can become flexible again. Center: A detail of her lab setup. Right: A sample of her super-strong yet recyclable plastic.

WINNI WINTERMEYER

JEANNETTE GARCIA

A chance discovery sparked a quest for plastics that are both strong and recyclable.

If Jeannette "Jamie" Garcia hadn't been so obsessed with understanding what things are made of, she probably would have "red-canned" her big discovery—that is, tossed it in the trash.

It was the young chemist's first week at **IBM**, and she had a simple task: mix three ingredients together in a flask and heat them up, the goal being to use one of those ingredients—a solution made from broken-down plastic bottles—as the basis for an even stronger material. After she combined the first two ingredients, she went off to weigh out the third. By the time she got back, the solution had solidified into something so hard that she needed a hammer to break it free. "A lot of people would've considered it a failed experiment," Garcia says. But she adds: "I didn't really want to just drop it. I wanted to try to figure out what I had made."

It turned out that the plastic was not only much stronger than what she had originally been trying to make but entirely recyclable. Those properties made it a promising gateway to desirable new materials.

Plastics that harden when heated are nothing new; we use them in everything from electronics to airplanes. But these so-called thermosets are not remoldable once hardened and mostly end up as garbage because they are very difficult to recycle. The thermoset plastic that Garcia made, on the other hand, completely reverted to its base compound, or monomer, when soaked in acid. "As chemists," she says, "if we understand what we're doing well enough, then we can actually go in and undo it too, in just as efficient a way as we built it."

Now, with the right monomers and the right temperatures, Garcia can make both super-strong recyclable plastics and moldable gels that solidify in their desired shape under ultraviolet light. She has nicknamed the first class of materials Titan and the second one Hydro.

There's still work to do before they are ready for commercial applications. But now that we know recyclable thermosets are possible, Garcia says, we can think of how they might replace materials we've been using for decades.

—Suzanne Jacobs

GOZDE DURMUS

It's amazing what you can learn about a cell when you levitate it.

Cells that are dying, turning cancerous, or responding to drugs undergo physical changes. They might become stiffer or squishier. Or they might get heavier or lighter. The instruments for detecting these changes in individual cells are usually complex and expensive, which is why microbiologists still assess the state of a disease by waiting for cells to grow in a lab, and why doctors examine whether a drug is working by waiting to see whether the patient worsens or improves.

Gozde Durmus has invented a simple, fast method for detecting cells' telling physical characteristic: making them levitate in a magnetic field and measuring how high they rise. White blood cells, red blood cells, cancer cells, and different bacteria each rise to a different height, because they have a characteristic density that determines the balance between the pull of gravity on the cell and the push of the magnetism. And Durmus has found that when a bacterial cell has responded to an antibiotic, it tends not to rise as high in the magnetic field as it did before. This change can be detected in about an hour, instead of the day traditionally required to determine how a microbe responds to a drug.

At her bench at the **Stanford** Genome Technology Center, Durmus makes cell-levitating devices by sliding a few laser-cut pieces of plastic over two small bar magnets. This keeps them from flipping and sticking together, so a magnetic field can be created in the space between them. She puts a thin capillary tube into that space. Then she adds two mirrors that will beam an image of the tube up to a conventional microscope. Samples of the cells to be levitated go into the tube along with a solution of gadolinium, an element that's used as an MRI contrast agent. "It helps the cells fly in the magnetic field," says Durmus. Their height can then be measured under the microscope.

Durmus knows from experience how important rapid, personalized drug monitoring could be. When she was a child in İzmir, Turkey, she had a bacterial infection that lasted three years, and she vividly remembers going to the hospital for painful and ineffective penicillin shots until she got the right treatment.

Durmus says it costs her less than $1 to make the magnetic "microgravity on a chip" cell detector.

Her work also has a more whimsical inspiration. In 1997, physicists in the Netherlands used an ultrastrong magnet to levitate a living frog. Subsequent efforts to levitate things in weak magnetic fields—even objects much smaller than frogs—required toxic magnetic solvents. Durmus figured out how to do levitation without toxic materials, using only cheap magnets and some pieces of plastic.

—Katherine Bourzac

Pioneers

MICHELLE O'MALLEY

Understanding a tricky kind of single-cell creature could help reduce the cost of biofuels.

Chemical engineer Michelle O'Malley is trying to figure out how an understudied type of microbe could be harnessed to make better biofuels or pharmaceuticals. O'Malley works with anaerobic microbes—organisms that can't live in the presence of oxygen, making them extremely difficult to cultivate. In fact, her lab at the **University of California, Santa Barbara**, is the only one in the United States that is able to study the behavior of anaerobic microbial communities.

Why go to all the trouble? Because these organisms are more efficient than aerobic ones at chewing up plant material and secreting something else, like a biofuel. They also create fewer unintended by-products, which are costly to deal with.

To study microbial communities, O'Malley combines a 1970s cultivation method with today's genome sequencing technology.

O'Malley is particularly interested in how different kinds of anaerobic microbes function in concert. Sometimes in such communities, whether in landfills or our guts, microbes work together to attack substances in their midst, while other times they interact peacefully with their environment. Their behavior, it seems, is determined by a complex communication system: microbes can physically attach to each other and exchange nutrients, or they can secrete chemicals into the environment that another microbe can metabolize.

Understanding this process is the first step in getting anaerobic microbes to churn out more cost-effective fuels or pharmaceutical products—and things we can't yet imagine. After all, O'Malley explains, many of the enzymes produced in anaerobic microbe communities "perform chemistries never seen before."

—Julia Sklar

GILAD EVRONY

Single-neuron genome sequencing is revealing clues about what goes wrong in the brain.

From studying 300 neurons one at a time, **Harvard Medical School** researcher Gilad Evrony helped make a surprising discovery: brain cells sitting right next to each other don't always have the same genetic codes. This could provide insight into age-related cognitive decline and brain disorders such as epilepsy and schizophrenia.

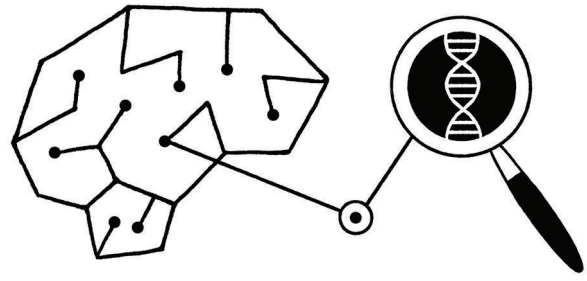
When scientists sequence DNA, they typically examine genetic material from thousands or millions of cells at a time. Decoding the genome of an individual cell is more challenging. Although researchers had done it with cells from other parts of the body, Evrony developed a way to do it with neurons from cadavers. Then he painstakingly mapped the origins of the mutations he found.

The implications are remarkable. For one thing, finding out the precise location of mutations indicates that some psychiatric diseases and mental disorders can be traced back to just a few bad neurons. Crucially, such mutations apparently are not inherited and don't arise during the brain's initial development. Instead, they crop up in brain cells during our lifetimes—and accumulate as we age. The rate at which those errors occur is not clear, though, and figuring that out could help explain how cognitive decline sets in and how it might be staved off.

Evrony took three and a half years off in the middle of college at MIT to serve in an intelligence unit of the Israeli military.

Such insights appear to be just the beginning of what we might discover by analyzing individual neurons. The National Institutes of Health has organized a consortium of labs that will study several mental disorders using this method, among others. Evrony calls the technology "the brain's new microscope."

—Julia Sklar



MIGUEL PORLAN

Humanitarians

Using technology to tackle problems caused by poverty, war, or disability.

MAGOZ

YEVGEN BORODIN

A software tool conceived for blind people could offer an intuitive way for anyone to listen to online material.

Yevgen Borodin, an assistant professor at **Stony Brook University** and CEO of Charmtech Labs, is making it easier for people who are blind—and everyone else, too—to listen to content published only as text online.

Borodin's software, Capti Narrator, serves as a hub for spoken material drawn from many written sources: Dropbox, Google Drive, Web pages, e-book repositories such as Bookshare and Gutenberg, and more. To create the software, Borodin and his team at Charmtech devised ways of extracting content from documents and websites and running it through text-to-speech engines. The software also lets users start listening on one device and continue on another, picking up where they left off.

Borodin has published more than 50 research papers on nonvisual interaction with computers.

"Blind people easily [take] far longer to do simple computer tasks than others do, and I decided that I had to do something about it," says Borodin, who grew up in Ukraine and came to the United States for college. His ultimate goal is for his invention to follow the path of assistive technologies such as optical character recognition and speech-to-text, which started out as niche tools for people with disabilities but became mainstream. Capti Narrator was unveiled at the 2014 Consumer Electronics Show and has been downloaded hundreds of thousands of times worldwide.

—David Talbot

Humanitarians

Rebecca Steorts Big data could cut through the fog of war.

Problem:
Determining the number of people killed in wars is immensely difficult: chaos, poor communication, and propaganda can wildly distort the figures.

Solution:
Rebecca Steorts, an assistant professor of statistics at **Duke University**, is using advanced data-analysis techniques to help human rights groups get definitive casualty counts.

Since the Syrian civil war began in 2011, six private organizations have been building databases of death totals. There is also an "official" governmental tally. But compiling them into one master document is a data nightmare because of duplicates, misspelled names, inaccurate dates, and even wrong genders. One estimate showed that running a basic comparison algorithm on the combined lists would take 57 days. In 2013, Steorts realized that by combining a Bayesian statistical approach with a machine-learning technique called blocking, she could reliably merge the databases—and do it in less than a day.

Blocking works by placing items that are similar to one another—say, similar names or approximate dates of death—in the same group for comparison. (A simple analogy: if you were trying to compile one whole set of cards out of two incomplete decks, you'd separate them into suits first and then discard the duplicates.) Only after it has assembled the various blocks does Steorts's software do the intensive work of linking individual records.

The Human Rights Data Analysis Group, a nonprofit that publishes a death toll for Syria once every year, is testing Steorts's method to see if it can be incorporated into the estimate it will release in 2016. *—Patrick Doyle*

SAURABH SRIVASTAVA

Voice and gestural interfaces could make digital technologies available to the world's poorest people.

More than 750 million people lack basic reading and writing skills. Saurabh Srivastava, a researcher at **Xerox India**, has been prolific in crafting technologies that could eventually make it easy for people with limited literacy to obtain information and use online services by simply speaking into phones or making gestures picked up by inexpensive cameras.

Building such interfaces is very hard because of the wide variation in cultural norms, not to mention languages and dialects. In some of his most recent work, in the rural Assam province, Srivastava investigated a system pregnant women might use to disclose medical problems to a Web interface that could refer them to free tests and services. The system used a $150 Microsoft Kinect camera to detect arm gestures, which in turn controlled displays of information. The display included animated representations of female health aides to guide the patients. Among the findings: the system should not require any gestural input that involves shoulder movements, since shoulders were often obscured by the women's saris. And when indicating medical complaints (say, a headache), women didn't understand why they should point to an on-screen picture of a head, but instead would point to their own head.

Improving health services this way could make a dent in big problems—such as the fact that nearly 63,000 women in India die in childbirth every year. *—David Talbot*

DUYGU KAYAMAN

What her parents did for her, she hopes to do for many other blind people.

Turkey is a tough place to live without sight. A dearth of social services and education for blind children means families often seclude them at home. Daily activities are riddled with peril: in cities, shoddily built sidewalks are littered with broken paving stones and sudden drop-offs. Gainful employment is a distant aspiration for many.

Duygu Kayaman lost her vision to an optic nerve tumor at two and a half. Growing up in Istanbul, she was determined to attend school with seeing students, but the lack of textbooks for the blind made it hard for her to compete. Her parents spent evenings and weekends dictating lessons into a tape recorder to help her keep up.

Those homemade audio books later inspired Kayaman to develop a mobile-phone application, Hayal Ortağım (My Dream Partner), to make daily activities easier for the visually impaired. It offers news and editorial columns through text-to-speech technology. Books, courses from the Khan Academy, and chess and guitar lessons are at hand. Location services help users find pharmacies and hospitals, and navigation systems for indoor spaces guide them through shopping centers; airports and subways are to be added soon. Also in

the works is a function for restaurants: it will alert staff through a Bluetooth beacon that a blind customer has arrived, and then transcribe the menu for the patron.

Some 150,000 Turks use My Dream Partner, out of an estimated visually impaired population of 700,000. Kayaman developed it with other vision-impaired members of an Istanbul-based organization, Young Guru Academy, and the support of Turkey's biggest mobile-phone operator, Turkcell.

Today she works as a sales specialist for **Microsoft** while studying for her MBA at Istanbul's Bilgi University. "It is only recently that people with disabilities are being hired by corporate firms," she says. "Managers simply did not know that a person with blindness or another physical disability could work in these environments. My friends and I are breaking down those stereotypes." *—Ayla Jean Yackley*

"My philosophy," Kayaman says, "is that life is beautiful, despite its obstacles."

MIKHAIL GALUSTOV

Rahul Panicker

This engineer from India returned home after graduate school with a new approach to helping premature babies.

"Humanity has known for over 100 years that keeping premature babies warm dramatically increases their survival rates. Yet most vulnerable babies around the world don't benefit from this knowledge.

"In 2007 I and three classmates at Stanford were encouraged to do fieldwork in Nepal. The first thing we realized was that low cost is not always the solution. Donated incubators were being used as filing cabinets, because there wasn't the electricity or the expertise to use them. Secondly, we found that parents desperate to keep their children alive were the users we should focus on, rather than doctors.

"We needed to reframe the problem. So we came up with a prototype incubator that costs 1 percent as much as traditional solutions and can be operated by a non-expert. It uses phase-change materials to keep babies at the ideal temperature of 37 °C for up to six hours without electricity. When heated with hot water or another source, a phase-change material melts, and it can release heat the baby needs at a constant temperature.

"NGOs we'd partnered with passed on the design. We realized if we didn't take this forward, no one else would. After a year of working on the project in my free time, we finally had our seed capital, and in 2009 I quit my job, moved to Bangalore with my three cofounders, and started **Embrace**. Since then our warmers have been used in 15 countries to help nearly 200,000 babies. We've implemented a hybrid for-profit/not-for-profit business model that lets us scale much faster than a charity.

"I hope future generations look to us as role models and take inspiration to go down the route of social entrepreneurship. Too many young people, especially in India, don't take risks because they worry about their futures. But I realized many years ago that someone with my education was never going to starve."

—as told to Edd Gent

Inside Amazon

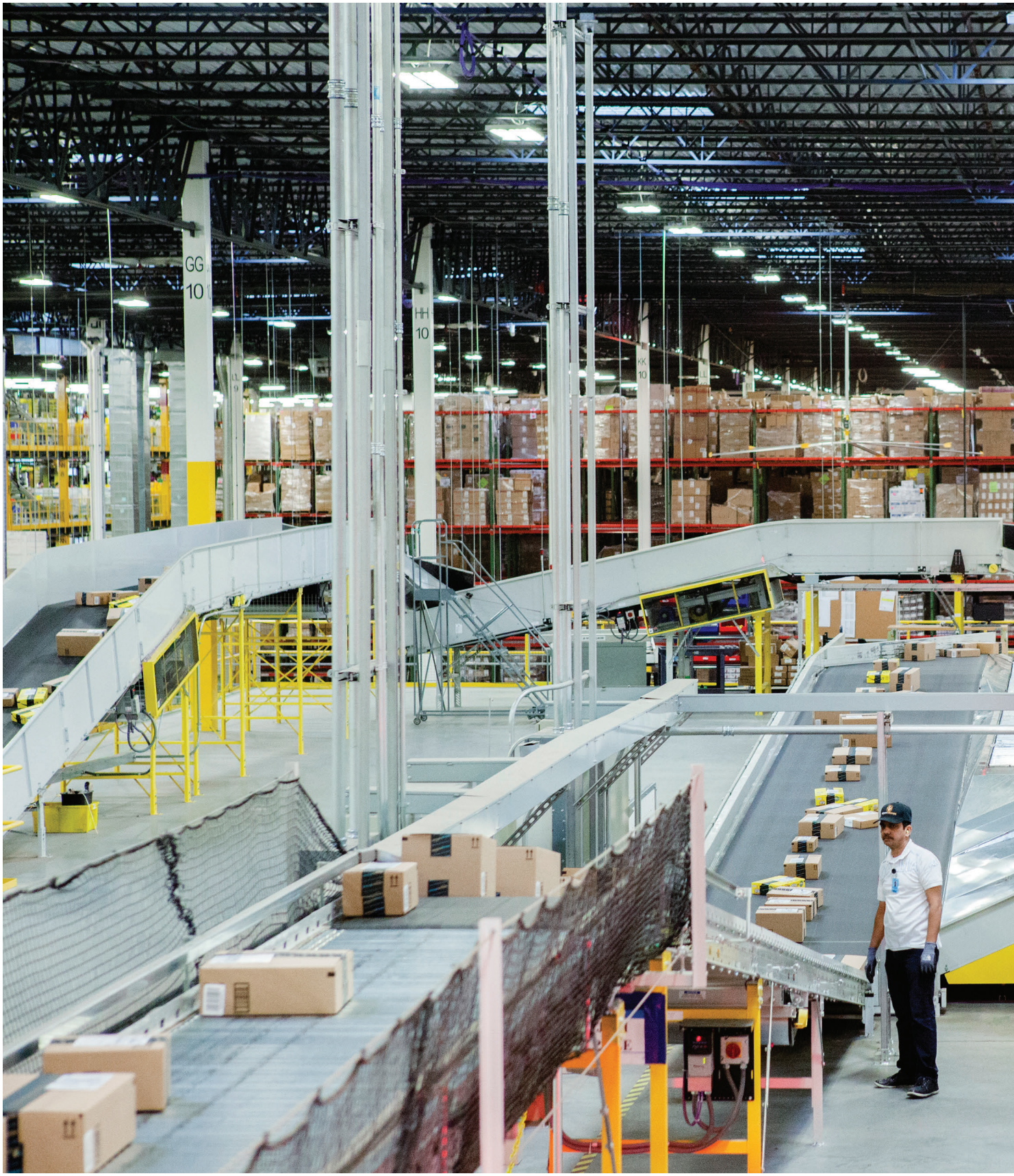
At a new fulfillment center in New Jersey, humans and robots work together in a highly efficient system.

Product labels are scanned so that boxes are automatically directed to the correct dispatch truck.

MIT TECHNOLOGY REVIEW
VOL. 118 | NO. 5

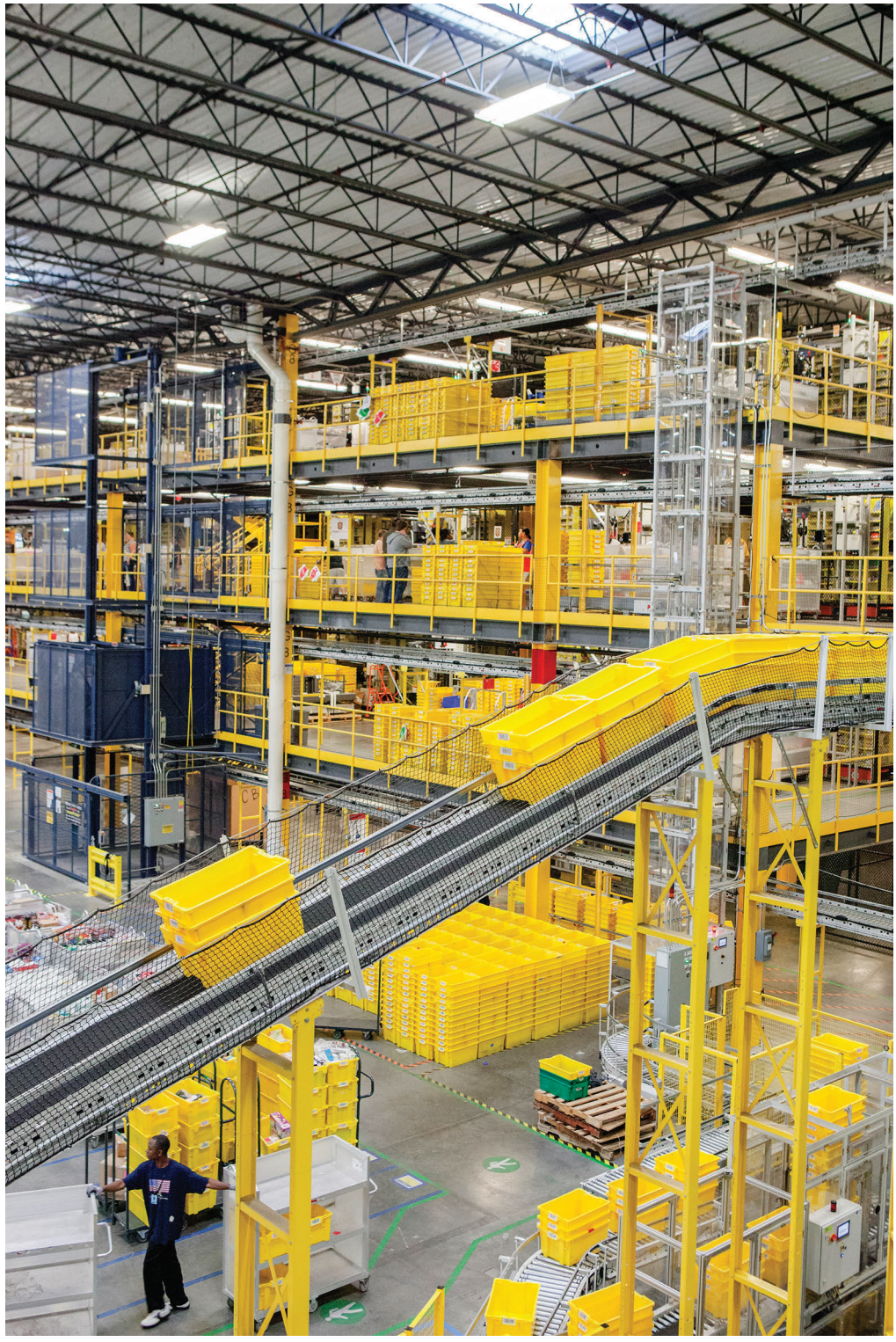
inside zone

Photographs by Lauren Lancaster


GG
10
HH
10
KK
10

MIT TECHNOLOGY REVIEW
VOL. 118 | NO. 5

A worker checks shipping boxes headed toward a bank of waiting trucks. The boxes are automatically sorted according to their destination.



Loose products move through Amazon's center in yellow crates.

Top: One worker retrieves products from a robotic shelf. Bottom: Another sorts crates.

Some of the secrets behind Amazon's phenomenal success as an online retailer can be discovered inside a million-square-foot warehouse that sits amid bucolic scenery in the town of Robbinsville, New Jersey. The building is one of Amazon's most advanced fulfillment centers, and it houses technologies that allow the company to deliver products to customers at amazing speed. Goods are identified, sorted, and packaged with computer-assisted precision, while employees work in tight collaboration with the plant's automated systems in shifts that run around the clock.

Upon arrival, each new product is identified using a computer vision system that catalogues it rapidly, feeding its weight and dimensions into a central tracking system. At the heart of the building, items stored on tall, square shelves are kept stocked by humans working with a team of 2,000 squat orange robots. The robots zip around the storage area, picking up shelves and either arranging them in neat rows for storage or bringing them over to the human workers, who stack or pick from them. Further along the fulfillment line, workers charged with packing up orders for shipping are automatically given the optimal size of shipping box and even the correct amount of packing tape. Before those boxes are sent to trucks, a system weighs them to make sure the correct products are inside. *—Will Knight*

The crates carrying products destined for Amazon's customers travel more than eight miles on conveyors that stretch throughout the building.


E
4

MIT TECHNOLOGY REVIEW
VOL. 118 | NO. 5

The blunt and puckish LeCun has a second opportunity to significantly advance artificial intelligence.

THOMAS EHRETSMANN

Teaching Machines to Understand Us

A reincarnation of one of the oldest ideas in artificial intelligence could finally make it possible to truly converse with our computers. And Facebook has a chance to make it happen first.

By Tom Simonite

The first time Yann LeCun revolutionized artificial intelligence, it was a false dawn. It was 1995, and for almost a decade, the young Frenchman had been dedicated to what many computer scientists considered a bad idea: that crudely mimicking certain features of the brain was the best way to bring about intelligent machines. But LeCun had shown that this approach could produce something strikingly smart—and useful. Working at Bell Labs, he made software that roughly simulated neurons and learned to read handwritten text by looking at many different examples. Bell Labs' corporate parent, AT&T, used it to sell the first machines capable of reading the handwriting on checks and written forms. To LeCun and a few fellow believers in artificial neural networks, it seemed to mark the beginning of an era in which machines could learn many other skills previously limited to humans. It wasn't.

"This whole project kind of disappeared on the day of its biggest success," says LeCun. On the same day he celebrated the launch of bank machines that could read thousands of checks per hour, AT&T announced it was splitting into three companies dedicated to different markets in communications and computing. LeCun became head of research at a slimmer AT&T and was directed to work on other things; in 2002 he would leave AT&T, soon to become a professor at New York University. Meanwhile, researchers elsewhere found that they could not apply LeCun's breakthrough to other computing problems. The brain-inspired approach to AI went back to being a fringe interest.

LeCun, now a stocky 55-year-old with a ready smile and a sideways sweep of dark hair touched with gray, never stopped pursuing that fringe interest. And remarkably, the rest of the world has come around. The ideas that he and a few others nurtured in the face of over two decades of apathy and sometimes outright rejection have in the past few years produced striking results in areas like face and speech recognition. Deep learning, as the field is now known, has become a new battleground between Google and other leading technology companies that are racing to use it in consumer services. One such company is Facebook, which hired LeCun from NYU in December 2013 and put him in charge of a new artificial-intelligence research group, FAIR, that today has 50 researchers but will grow to 100. LeCun's lab is Facebook's first significant investment in fundamental research, and it could be crucial to the company's attempts to become more than just a virtual social venue. It might also reshape our expectations of what machines can do.

Facebook and other companies, including Google, IBM, and Microsoft, have moved quickly to get into this area in the past few years because deep learning is far better than previous AI techniques at getting computers to pick up skills that challenge machines, like understanding photos. Those more established techniques require human experts to laboriously program certain abilities, such as how to detect lines and corners in images. Deep-learning software figures out how to make sense of data for itself, without any such programming. Some systems can now recognize images or faces about as accurately as humans.

Now LeCun is aiming for something much more powerful. He wants to deliver software with the language skills and common sense needed for basic conversation. Instead of having to communicate with machines by clicking buttons or entering carefully chosen search terms, we could just tell them what we want as if we were talking to another person. "Our relationship with the digital world will completely change due to intelligent agents you can interact with," he predicts. He thinks deep learning can produce software that understands our sentences and can respond with appropriate answers, clarifying questions, or suggestions of its own.

Agents that answer factual questions or book restaurants for us are one obvious—if not exactly world-changing—application. It's also easy to see how such software might lead to more stimulating video-game characters or improve online learning. More provocatively, LeCun says systems that grasp ordinary language could get to know us well enough to understand what's good for us. "Systems like this should be able to understand not just what people would be entertained by but

asdfasdf

Deep Learning's Leaders

Geoff Hinton
Google and the University of Toronto
Did his PhD on artificial neural networks in the 1970s. Showed how to train larger, "deep" neural networks on large data sets in the 2000s, and proved their power for speech and image recognition.

Yann LeCun
Facebook
Got interested in neural networks as an undergraduate, and later pioneered the use of deep learning for image recognition. Now leads a group at Facebook trying to create software that understands text and can hold conversations.

Yoshua Bengio
University of Montreal
Started working on artificial neural networks after meeting LeCun at Bell Labs in the 1980s. Was one of the first to apply the technique to understanding words and language. Now working with IBM to improve its Watson software.

Andrew Ng
Baidu
Led a project at Google that worked out how neural networks could be trained on millions of pieces of data, allowing greater accuracy. Now oversees research at Baidu, which is working on improved speech recognition.

Demis Hassabis
DeepMind
Worked on AI in the games industry, then researched neuroscience to get ideas about building intelligence. He founded DeepMind, which Google bought last year and runs as a quasi-independent unit.

what they need to see regardless of whether they will enjoy it," he says. Such feats aren't possible using the techniques behind the search engines, spam filters, and virtual assistants that try to understand us today. They often ignore the order of words and get by with statistical tricks like matching and counting keywords. Apple's Siri, for example, tries to fit what you say into a small number of categories that trigger scripted responses. "They don't really understand the text," says LeCun. "It's amazing that it works at all." Meanwhile, systems that seem to have mastered complex language tasks, such as IBM's *Jeopardy!* winner Watson, do it by being super-specialized to a particular format. "It's cute as a demonstration, but not work that would really translate to any other situation," he says.

In contrast, deep-learning software may be able to make sense of language more the way humans do. Researchers at Facebook, Google, and elsewhere are developing software that has shown progress toward understanding what words mean. LeCun's team has a system capable of reading simple stories and answering questions about them, drawing on faculties like logical deduction and a rudimentary understanding of time.

However, as LeCun knows firsthand, artificial intelligence is notorious for blips of progress that stoke predictions of big leaps forward but ultimately change very little. Creating software that can handle the dazzling complexities of language is a bigger challenge than training it to recognize objects in pictures. Deep learning's usefulness for speech recognition and image detection is beyond doubt, but it's still just a guess that it will master language and transform our lives more radically. We don't yet know for sure whether deep learning is a blip that will turn out to be something much bigger.

Deep history

The roots of deep learning reach back further than LeCun's time at Bell Labs. He and a few others who pioneered the technique were actually resuscitating a long-dead idea in artificial intelligence.

When the field got started, in the 1950s, biologists were just beginning to develop simple mathematical theories of how intelligence and learning emerge from signals passing between neurons in the brain. The core idea—still current today—was that the links between neurons are strengthened if those cells communicate frequently. The fusillade of neural activity triggered by a new experience adjusts the brain's connections so it can understand it better the second time around.

In 1956, the psychologist Frank Rosenblatt used those theories to invent a way of making simple simulations of neurons in software and hardware. The *New York Times* announced his work with the headline "Electronic 'Brain' Teaches Itself." Rosenblatt's perceptron, as he called his design, could learn how to sort simple images into categories—for instance, triangles and squares. Rosenblatt usually implemented his ideas on giant machines thickly tangled with wires, but they established the basic principles at work in artificial neural networks today.

One computer he built had eight simulated neurons, made from motors and dials connected to 400 light detectors. Each of the neurons received a share of the signals from the light detectors, combined them, and, depending on what they added up to, spit out either a *1* or a *0*. Together those digits amounted to the perceptron's "description" of what it saw. Initially the results were garbage. But Rosenblatt used a method called supervised learning to train a perceptron to generate results that correctly distinguished different shapes. He would show

Deep learning is good at taking dictation and recognizing images. But can it master human language?

the perceptron an image along with the correct answer. Then the machine would tweak how much attention each neuron paid to its incoming signals, shifting those "weights" toward settings that would produce the right answer. After many examples, those tweaks endowed the computer with enough smarts to correctly categorize images it had never seen before. Today's deep-learning networks use sophisticated algorithms and have millions of simulated neurons, with billions of connections between them. But they are trained in the same way.

Rosenblatt predicted that perceptrons would soon be capable of feats like greeting people by name, and his idea became a linchpin of the nascent field of artificial intelligence. Work focused on making perceptrons with more complex networks, arranged into a hierarchy of multiple learning layers. Passing images or other data successively through the layers would allow a perceptron to tackle more complex problems. Unfortunately, Rosenblatt's learning algorithm didn't work on multiple layers. In 1969 the AI pioneer Marvin Minsky, who had gone

to high school with Rosenblatt, published a book-length critique of perceptrons that killed interest in neural networks at a stroke. Minsky claimed that getting more layers working wouldn't make perceptrons powerful enough to be useful. Artificial-intelligence researchers abandoned the idea of making software that learned. Instead, they turned to using logic to craft working facets of intelligence—such as an aptitude for chess. Neural networks were shoved to the margins of computer science.

Nonetheless, LeCun was mesmerized when he read about perceptrons as an engineering student in Paris in the early 1980s. "I was amazed that this was working and wondering why people abandoned it," he says. He spent days at a research library near Versailles, hunting for papers published before perceptrons went extinct. Then he discovered that a small group of researchers in the United States were covertly working on neural networks again. "This was a very underground movement," he says. In papers carefully purged of words like "neural" and "learning" to avoid rejection by reviewers, they were working on something very much like Rosenblatt's old problem of how to train neural networks with multiple layers.

LeCun joined the underground after he met its central figures in 1985, including a wry Brit named Geoff Hinton, who now works at Google and the University of Toronto. They immediately became friends, mutual admirers—and the nucleus of a small community that revived the idea of neural networking. They were sustained by a belief that using a core mechanism seen in natural intelligence was the only way to build artificial intelligence. "The only method that we knew worked was a brain, so in the long run it had to be that systems something like that could be made to work," says Hinton.

LeCun's success at Bell Labs came about after he, Hinton, and others perfected a learning algorithm for neural networks with multiple layers. It was known as backpropagation, and it sparked a rush of interest from psychologists and computer scientists. But after LeCun's check-reading project ended, backpropagation proved tricky to adapt to other problems, and a new way to train software to sort data was invented by a Bell Labs researcher down the hall from LeCun. It didn't involve simulated neurons and was seen as mathematically more elegant. Very quickly it became a cornerstone of Internet companies such as Google, Amazon, and LinkedIn, which use it to train systems that block spam or suggest things for you to buy.

After LeCun got to NYU in 2003, he, Hinton, and a third collaborator, University of Montreal professor Yoshua Bengio, formed what LeCun calls "the deep-learning conspiracy." To prove that neural networks would be useful, they quietly developed ways to make them bigger, train them with larger data sets, and run them on more powerful computers. LeCun's handwriting recognition system had had five layers of neurons, but now they could have 10 or many more. Around 2010, what was now dubbed deep learning started to beat established techniques on real-world tasks like sorting images. Microsoft, Google, and IBM added it to speech recognition systems. But neural networks were still alien to most researchers and not considered widely useful. In early 2012 LeCun wrote a fiery letter—initially published anonymously—after a paper claiming to have set a new record on a standard vision task was rejected by a leading conference. He accused the reviewers of being "clueless" and "negatively biased."

Everything changed six months later. Hinton and two grad students used a network like the one LeCun made for reading checks to rout the field in the leading contest for image recognition. Known as the ImageNet Large Scale Visual Recognition Challenge, it asks software to identify 1,000 types of objects as diverse as mosquito nets and mosques. The Toronto entry correctly identified the object in an image within five guesses about 85 percent of the time, more than 10 percentage points better than the second-best system (see Innovator Under 35 Ilya Sutskever, page 47). The deep-learning soft-

Journey to Acceptance

1956: Psychologist Frank Rosenblatt uses theories about how brain cells work to design the perceptron, an artificial neural network that can be trained to categorize simple shapes.

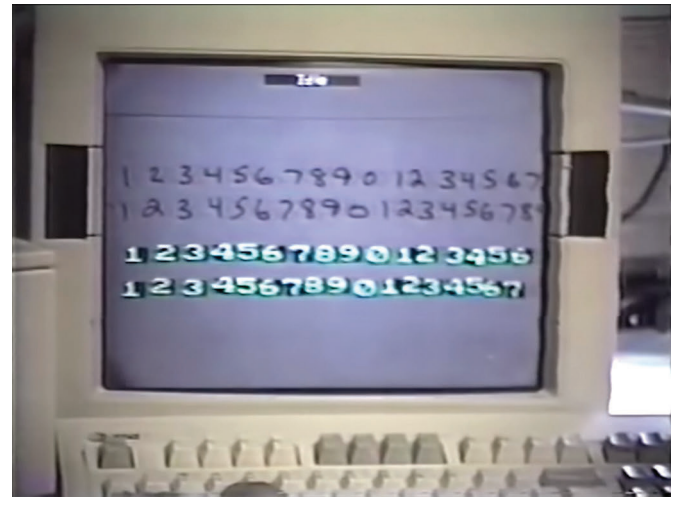
1969: AI pioneers Marvin Minsky and Seymour Papert write a book critical of perceptrons that quashes interest in neural networks for decades.

1986: Yann LeCun and Geoff Hinton perfect backpropagation to train neural networks that pass data through successive layers of artificial neurons, allowing them to learn more complex skills.

1987: Terry Sejnowski at Johns Hopkins University creates a system called NETtalk that can be trained to pronounce text, going from random babbling to recognizable speech.

1990: At Bell Labs, LeCun uses backpropagation to train a network that can read handwritten text. AT&T later uses it in machines that can read checks.

1995: Bell Labs mathematician Vladimir Vapnik publishes an alternative method for training software to categorize data such as images. This sidelines neural networks again.



LeCun at Bell Labs in 1993, with a computer that could read the handwriting on checks.

ware's initial layers of neurons optimized themselves for finding simple things like edges and corners, with the layers after that looking for successively more complex features like basic shapes and, eventually, dogs or people.

LeCun recalls seeing the community that had mostly ignored neural networks pack into the room where the winners presented a paper on their results. "You could see right there a lot of senior people in the community just flipped," he says. "They said, 'Okay, now we buy it. That's it, now—you won.'"

Academics working on computer vision quickly abandoned their old methods, and deep learning suddenly became one of the main strands in artificial intelligence. Google bought a company founded by Hinton and the two others behind the 2012 result, and Hinton started working there part time on a research team known as Google Brain. Microsoft and other companies created new projects to investigate deep learning. In December 2013, Facebook CEO Mark Zuckerberg stunned academics by showing up at the largest neural-network research conference, hosting a party where he announced that LeCun was starting FAIR (though he still works at NYU one day a week).

LeCun still harbors mixed feelings about the 2012 research that brought the world around to his point of view. "To some extent this should have come out of my lab," he says. Hinton shares that assessment. "It was a bit unfortunate for Yann that he wasn't the one who actually made the breakthrough system," he says. LeCun's group had done more work than anyone else to prove out the techniques used to win the ImageNet challenge. The victory could have been his had student gradua-

2006: Hinton's research group at the University of Toronto develops ways to train much larger networks with tens of layers of artificial neurons.

June 2012: Google uses deep learning to cut the error rate of its speech recognition software by 25 percent.

October 2012: Hinton and two colleagues from the University of Toronto win the largest challenge for software that recognizes objects in photos, almost halving the previous error rate.

March 2013: Google buys DNN Research, the company founded by the Toronto team to develop their ideas. Hinton starts working at Google.

March 2014: Facebook starts using deep learning to power its facial recognition feature, which identifies people in uploaded photos.

May 2015: Google Photos launches. The service uses deep learning to group photos of the same people and let you search your snapshots using terms like "beach" or "dog."

COURTESY OF FACEBOOK

tion schedules and other commitments not prevented his own group from taking on ImageNet, he says. LeCun's hunt for deep learning's next breakthrough is now a chance to even the score.

Language learning

Facebook's New York office is a three-minute stroll up Broadway from LeCun's office at NYU, on two floors of a building constructed as a department store in the early 20th century. Workers are packed more densely into the open plan than they are at Facebook's headquarters in Menlo Park, California, but they can still be seen gliding on articulated skateboards past notices for weekly beer pong. Almost half of LeCun's team of leading AI researchers works here, with the rest at Facebook's California campus or an office in Paris. Many of them are trying to make neural networks better at understanding language. "I've hired all the people working on this that I could," says LeCun.

A neural network can "learn" words by spooling through text and calculating how each word it encounters could have been predicted from the words before or after it. By doing this, the software learns to represent every word as a vector that indicates its relationship to other words—a process that uncannily captures concepts in language. The difference between the vectors for "king" and "queen" is the same as for "husband" and "wife," for example. The vectors for "paper" and "cardboard" are close together, and those for "large" and "big" are even closer.

The same approach works for whole sentences (Hinton says it generates "thought vectors"), and Google is looking at using it to bolster its automatic translation service. A recent paper from researchers at a Chinese university and Microsoft's Beijing lab used a version of the vector technique to make software that beats some humans on IQ-test questions requiring an understanding of synonyms, antonyms, and analogies.

Several companies have opened deep-learning labs. "I've hired all the people working on this that I could," says LeCun.

LeCun's group is working on going further. "Language in itself is not that complicated," he says. "What's complicated is having a deep understanding of language and the world that gives you common sense. That's what we're really interested in building into machines." LeCun means common sense as Aristotle used the term: the ability to understand basic physical reality. He wants a computer to grasp that the sentence "Yann picked up the bottle and walked out of the room" means the bottle left with him. Facebook's researchers have invented a deep-learning system called a memory network that displays what may be the early stirrings of common sense.

A memory network is a neural network with a memory bank bolted on to store facts it has learned so they don't get washed away every time it takes in fresh data. The Facebook AI lab has created versions that can answer simple common-sense questions about text they have never seen before. For example, when researchers gave a memory network a very simplified summary of the plot of *Lord of the Rings*, it could answer questions such as "Where is the ring?" and "Where was Frodo before Mount Doom?" It could interpret the simple world described in the text despite having never previously encountered many of the names or objects, such as "Frodo" or "ring."

The software learned its rudimentary common sense by being shown how to answer questions about a simple text in which characters do things in a series of rooms, such as "Fred moved to the bedroom and Joe went to the kitchen." But LeCun wants to expose the software to texts that are far better at capturing the complexity of life and the things a virtual assistant might need to do. A virtual concierge called Moneypenny that Facebook is expected to release could be one source of that data. The assistant is said to be powered by a team of human operators who will help people do things like make restaurant reservations. LeCun's team could have a memory network watch over Moneypenny's shoulder before eventually letting it learn by interacting with humans for itself.

Building something that can hold even a basic, narrowly focused conversation still requires significant work. For example, neural networks have shown only very simple reasoning, and researchers haven't figured out how they might be taught to make plans, says LeCun. But results from the work that has been done with the technology so far leave him confident about where things are going. "The revolution is on the way," he says.

Some people are less sure. Deep-learning software so far has displayed only the simplest capabilities required for what we would recognize as conversation, says Oren Etzioni, CEO of the Allen Institute for Artificial Intelligence in Seattle. The logic and planning capabilities still needed, he says, are very

It's not clear how much we'd benefit from smarter virtual assistants, but we may not have to wait long to find out.

different from the things neural networks have been doing best: digesting sequences of pixels or acoustic waveforms to decide which image category or word they represent. "The problems of understanding natural language are not reducible in the same way," he says.

Gary Marcus, a professor of psychology and neural science at NYU who has studied how humans learn language and recently started an artificial-intelligence company called Geometric Intelligence, thinks LeCun underestimates how hard it would be for existing software to pick up language and common sense. Training the software with large volumes of carefully annotated data is fine for getting it to sort images. But Marcus doubts it can acquire the trickier skills needed for language, where the meanings of words and complex sentences can flip depending on context. "People will look back on deep learning and say this is a really powerful technique—it's the first time that AI became practical," he says. "They'll also say those things required a lot of data, and there were domains where people just never had enough." Marcus thinks language may be one of those domains. For software to master conversation, it would need to learn more like a toddler who picks it up without explicit instruction, he suggests.

Deep belief

At Facebook's headquarters in California, the West Coast members of LeCun's team sit close to Mark Zuckerberg and Mike Schroepfer, the company's CTO. Facebook's leaders know that LeCun's group is still some way from building something you can talk to, but Schroepfer is already thinking about how to use it. The future Facebook he describes retrieves and coördinates information, like a butler you communicate with by typing or talking as you might with a human one.

"You can engage with a system that can really understand concepts and language at a much higher level," says Schroepfer. He imagines being able to ask that you see a friend's baby snapshots but not his jokes, for example. "I think in the near term a version of that is very realizable," he says. As LeCun's systems achieve better reasoning and planning abilities, he expects the conversation to get less one-sided. Facebook might offer up information that it thinks you'd like and ask what you thought of it. "Eventually it is like this super-intelligent helper that's plugged in to all the information streams in the world," says Schroepfer.

The algorithms needed to power such interactions would also improve the systems Facebook uses to filter the posts and ads we see. And they could be vital to Facebook's ambitions to become much more than just a place to socialize. As Facebook begins to host articles and video on behalf of media and entertainment companies, for example, it will need better ways for people to manage information. Virtual assistants and other spinouts from LeCun's work could also help Facebook's more ambitious departures from its original business, such as the Oculus group working to make virtual reality into a mass-market technology.

None of this will happen if the recent impressive results meet the fate of previous big ideas in artificial intelligence. Blooms of excitement around neural networks have withered twice already. But while complaining that other companies or researchers are over-hyping their work is one of LeCun's favorite pastimes, he says there's enough circumstantial evidence to stand firm behind his own predictions that deep learning will deliver impressive payoffs. The technology is still providing more accuracy and power in every area of AI where it has been applied, he says. New ideas are needed about how to apply it to language processing, but the still-small field is expanding fast as companies and universities dedicate more people to it. "That will accelerate progress," says LeCun.

It's still not clear that deep learning can deliver anything like the information butler Facebook envisions. And even if it can, it's hard to say how much the world really would benefit from it. But we may not have to wait long to find out. LeCun guesses that virtual helpers with a mastery of language unprecedented for software will be available in just two to five years. He expects that anyone who doubts deep learning's ability to master language will be proved wrong even sooner. "There is the same phenomenon that we were observing just before 2012," he says. "Things are starting to work, but the people doing more classical techniques are not convinced. Within a year or two it will be the end."

Tom Simonite is MIT Technology Review*'s San Francisco bureau chief.*

Learn from the same materials MIT students use in class.

MITOPENCOURSEWARE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

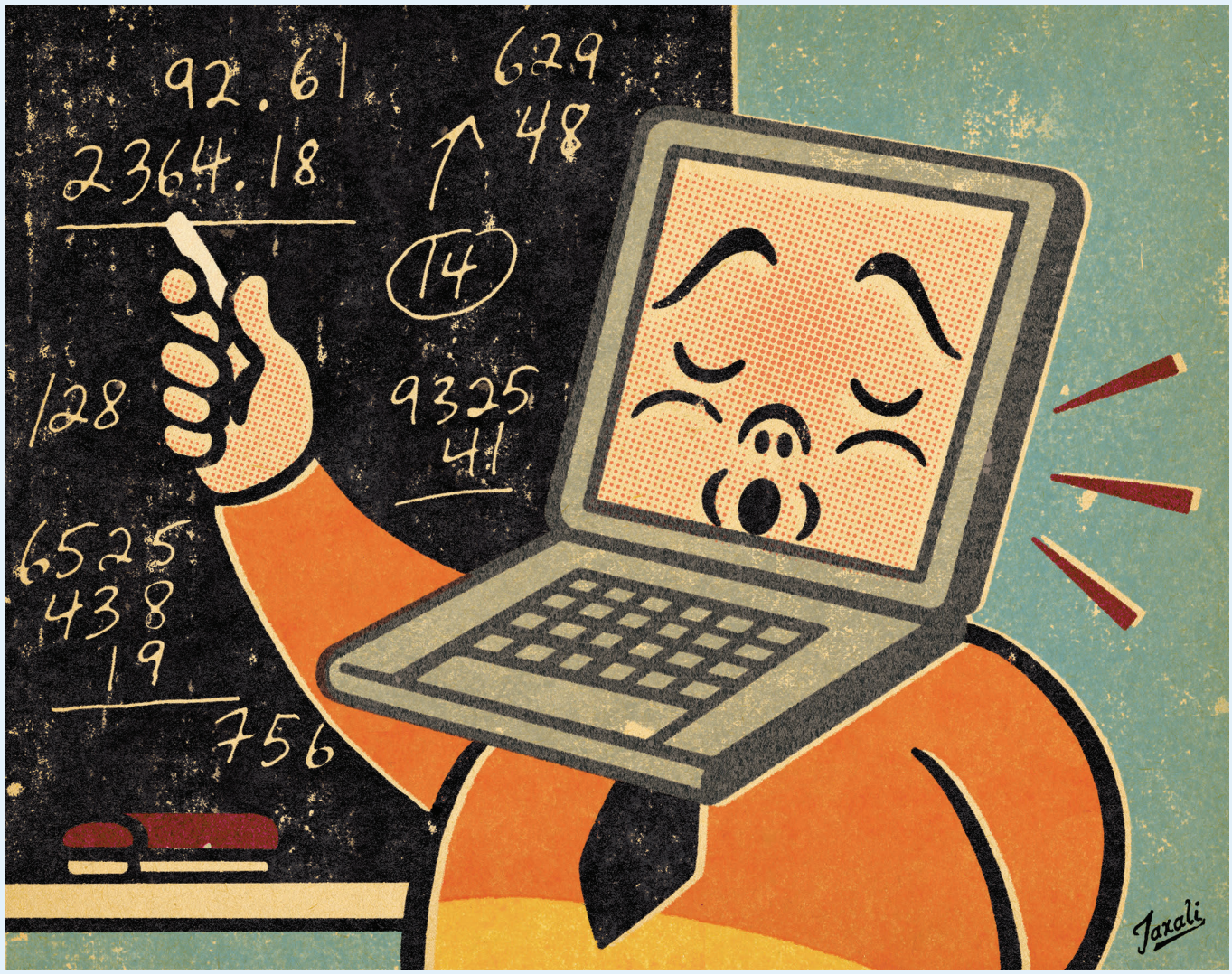
Online. All the time. Always free.
Keep learning at ocwscholar.mit.edu/tr

MIT Technology Review
BUSINESS REPORT

CONTENTS

Online Learning

Technology can now gather tremendous amounts of data about how we learn. What is that teaching us?



GARY TAXALI

The Big Question

Lessons from the Digital Classroom

Technologists and venture capitalists are betting that the data online learning generates will reshape education.

● In four small schools scattered across San Francisco, a data experiment is under way. That is where AltSchool is testing how technology can help teachers maximize their students' learning.

Founded two years ago by Max Ventilla, a data expert and former head of personalization at Google, AltSchool runs schools filled with data-gathering technology.

Information is captured from the moment each student arrives at school and checks in on an attendance app. For part of the day, students work independently, using iPads and Chromebooks, on "playlists" of activities that teachers have selected to match their personal goals. Data about each student's progress is captured for teachers' later review. Classrooms are recorded, and teachers can flag important moments by pressing a button, as you might TiVo your favorite television show.

The idea is that all the data from this network of schools will be woven into a smart centralized operating system that teachers will be able to use to design effective and personalized instruction. There is even a recommendation engine built in.

While most schools don't have the type of technology AltSchool is developing, classrooms are increasingly filled with laptops and other digital teaching aids. This year U.S. elementary, middle, and high schools are expected to spend $4.7 billion on information technology. What is new is that many of the technologies are capturing expansive amounts of data, enough of it to search for meaningful patterns and insight into how students learn. The potential for that to be turned into profit is a big reason investors have increased funding of educational technology startups worldwide, from $1.6 billion in 2013 to $2.4 billion in 2014; they invested over $1 billion more in the first quarter of 2015, much of that in China. What all that data is teaching us about how we learn and whether technology is actually making instruction better are the big questions at the heart of this Business Report.

At the AltSchools, where tuition can exceed $20,000 a year, the goal is to create highly individualized instruction built on a system that can grow to reach a broad scale. Four more AltSchools are opening this fall, including one in Brooklyn, New York, and Ventilla hopes to eventually sell access to the system to other schools, too. AltSchool has raised $133 million from the likes of Facebook founder Mark Zuckerberg, venture capitalist John Doerr, the Omidyar Network, and venture firms Andreessen Horowitz and Founders Fund. "What if we tried to create not just great schools we'd like to send our kids to, but an expanding ecosystem?" says Ventilla, who started thinking about education when he and his wife began applying to preschool for their daughter in 2012. "What role can technology play to superpower each child and each set of parents and educators?"

Similar experiments are under way in colleges as well. In the seven years since the first "massive open online course," Connectivism and Connective Knowledge, was taught by two Canadian educators, Stephen Downes and George Siemens, MOOCs have become a source of tremendous amounts of data about students' behavior. Examination of this data has intensified since 2012, when the three largest platforms for these classes were launched: the Harvard-MIT joint venture edX and two for-profit companies founded by former Stanford professors, Udacity and Coursera. Between the fall of 2012 and the summer of 2014, more than a million people participated in the 68 open online courses on edX, logging 1.1 billion clicks on the edX servers.

While only a small percentage of students complete any given MOOC, their data is helping educators develop new teaching models that promise to be more effective—such as programs that combine online instruction with one-on-one coaching or support, regular quizzes, and other check-ins on progress.

This approach has been shown in some cases to be more successful than traditional classroom instruction. Arizona State University, for example, offers more than 90 different undergraduate and graduate degrees online, part of a

Online Learning Over Time

An abbreviated history of learning over the Web.

1992
The Electronic University Network offers a PhD via America Online.

1996
Western Governors University, initially funded by 11 states, begins offering courses online. By 2015 its programs will graduate 10,000 students a year.

2003
Eighty-one percent of colleges offer at least one course online.

2008
First massive open online course (MOOC) is taught, and Salman Khan launches Khan Academy, the nonprofit free tutorial site.

2011
Sebastian Thrun and Peter Norvig's MOOC Introduction to Artificial Intelligence opens a Stanford classroom to the Web. Initial enrollment: over 150,000.

2012
The *New York Times* declares 2012 the "Year of the MOOC" after the launch of edX, a nonprofit joint venture of Harvard and MIT, and the private companies Udacity and Coursera.

2013
Georgia Institute of Technology offers first MOOC-based master's degree, in computer science.

2015
Arizona State University begins offering full freshman college credit for certain MOOCs.

long-term goal as a public university of expanding access to education. The university teaches freshman math to 8,000 students a year. Those needing to catch up to college level are placed in Developmental Math, a class where 50 percent of students have traditionally earned a D or F.

Four years ago ASU combined its online and classroom approaches to Developmental Math, switching to video-based lectures and incorporating an online tool made by a company called Knewton. It analyzes students as they work through online math lessons to understand how they learn best and what they have and have not mastered. Reports on students' progress, the time they are putting in, and their engagement and success then go to student coaches who reach out by e-mail, text message, or in person. In the first two semesters the school used this approach, the pass rate increased to 75 percent.

Udacity has similarly structured itself around individualized feedback. In its first month offering a "nanodegree" in Android programming, designed with Google, Udacity reported that students had submitted over 2,000 projects, which were then evaluated by a paid network of coding experts around the world. Cofounder Sebastian Thrun says 91 percent of paying students with this kind of coached model finish the course. Though it's not a perfect contrast, the free robotics MOOC Thrun taught as a Stanford professor had a completion rate of 2 percent.

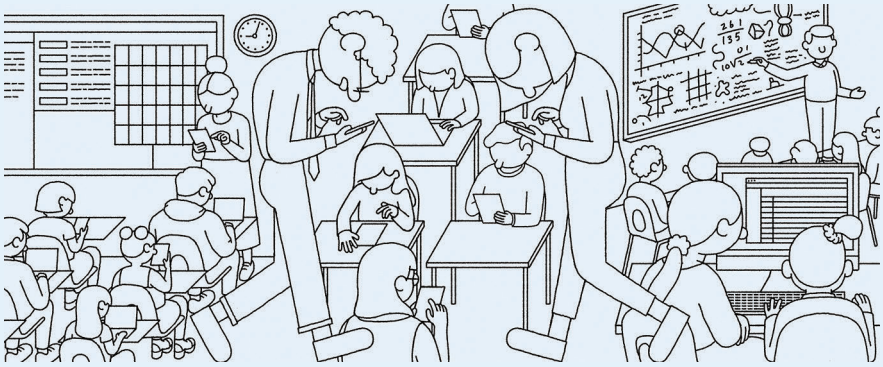
The data from online instruction offers a new level of feedback for teachers, too. Teachers on the Coursera platform have a dashboard on which they can see exactly when in a video students are most likely to stop watching, what percentage of students are getting an assessment question right the first time, and other metrics. If only 20 of the 200 students taking a quiz got a certain question right, teachers can reëxamine how they taught that point in the video or how the question was worded to see what's going wrong.

"I taught in a university 18 years and I never got that kind of detailed feedback," says Daphne Koller, a Stanford engineering professor who cofounded Coursera three years ago. *—Nanette Byrnes*

LAURIE ROLLITT

THE CONNECTED CLASSROOM

Online learning comes into the classroom. By Kristin Majcher



DIGITAL DOCUMENTS New apps and software platforms allow teachers to keep their student lists, attendance records, calendars, and correspondence all in one place. Google Classroom is one that allows students to hand in homework online and see their grade when the teacher is done reviewing it. Schoology is another popular example.

COMMUNICATION More than 20 percent of U.S. teachers use an app called Remind to text parents and students about deadlines without exposing personal information, according to the app maker. Pearson's PowerTeacher and PowerSchool apps give parents real-time feedback about their children's grades or behavior.

CLASS WEBSITES Teachers can make class websites using Haiku Learning or Google Sites without writing code. Many schools now make announcements on Facebook and Twitter. Science teacher Jessica Anderson at Powell County High School in Deer Lodge, Montana, uses the @SciencePCHS tag on Instagram, Twitter, and Vine to post class projects like a Rube Goldberg machine.

GAMING Students can earn points for good behavior on ClassDojo, or by answering questions on their smartphones in the Kahoot app, which claims 30 million users. Students playing ClassCraft use special powers to advance their team through a virtual world. Correct answers unlock perks like the right to ask questions during tests.

STUDENT DEVICES More and more schools aim to have a laptop or tablet for every student. The 435 students at Intrinsic, a charter school in Chicago, had Chromebooks last year. Powell County High School distributed laptops to students three years ago, switched to iPads this year, and will issue HP Stream laptops next year.

PROJECTS Students can map out writing assignments on iPads through Inspiration and upload notes into Google Drive with Notability. Writing.com's Writing Prompts app gives students ideas for essays, and Scholastic's Book Wizard helps students and teachers keep track of interesting books they would like to read.

CLASSROOM DESIGN Intrinsic divides its English and math classrooms into different areas. Students learn directly from teachers in one section, have group discussions on blue chairs in an area called the "ocean," work independently on the "coastline" (which snakes around the room's perimeter), and work in groups at tables in the "shade."

STREAMLINED SECURITY Protecting and securing student data is a growing concern. Through Clever, teachers decide which education tools can access encrypted student data and how much they can see. Clever, Apple, Google, and AT&T are a few of the 150 technology companies pledging to protect student data from being sold or used for advertising.

Q&A

The Believer: Duke's Sally Kornbluth

Duke's provost says there's no question that students are getting value from online learning.

● Of all the U.S. universities offering free online courses to the world, Duke University in Durham, North Carolina, is among the most active. Its professors have filled Coursera's distance-learning platform with 30 courses, in subjects ranging from astronomy to dog emotions. Since 2013, the university has assigned one administrator exclusively to digital and online education initiatives. There's even a collection of sunny haikus about online education on Duke's website.

"A few years ago, the question was 'Should we be teaching online or shouldn't we?' says Duke provost Sally Kornbluth, a geneticist by training. "That conversation has passed. Now it's a conversation about what kinds of innovative things we can do." In a discussion with *MIT Technology Review* contributing editor George Anders, Kornbluth explained why Duke is bullish about online education—and what new opportunities lie ahead.

Universities have been relying on books, lectures, and seminars since the 1400s. Does online learning provide a fourth channel that can rival the others?
It's supplementary. It hasn't replaced in-person lectures or books. But there's no question that students are finding it another avenue for getting the information they want. Frequently, that's complementary to traditional settings. In other words, they're looking for more background. Online learning actually enriches their in-person experience.

Tell me more about blended learning—where instructors use a mix of online tools and classroom settings. How much is that happening at Duke, and what are the results?
We have a lot of "flipped classroom" education going on. It's not in every corner of the university, but you will see plenty of situations where students do online exercises or watch material online ahead of class. Then faculty can use class time for experiential learning or discussions, rather than straight-on delivery of didactic material. Students still get in-person interactions with fellow students and the faculty. We create touch points that interface with the technology, rather than having the technology be stand-alone.

Which specific techniques in online education strike you as game changers?
I'm really interested in the trend toward bite-sized pieces of education. The first MOOCs were replicas of the traditional, full-semester experience. Now, though, we're seeing professors offer 15-minute modules, or three-week pop-up courses. People are experimenting with a lot of formats that break with traditional content delivery. In fact, I caught my son taking online physics courses at Yale, watching them at double speed.

What's the impact of MOOCs on the way your professors do their jobs?
At Duke, it's revitalized the notion of pedagogic innovation, in a way that's spilled out of the online space and into the regular classroom. You can take your base course, add some content, and then retailor it for alumni education or executive education. You can interact directly with people all over the world to address a common issue. Or if you're wondering how you can possibly read 400,000 essays, you can have 400,000 students read one another's essays. There's a lot of unexplored power that can be harnessed.

What are some issues associated with online learning that you haven't solved?
One of the things we haven't grappled with is how online teaching factors into things like promotions and tenure. Right now it doesn't have a formal role; it's still just an add-on. And at the undergraduate level, we aren't offering stand-alone online courses for credit. That would be a much more serious conversation that would involve a lot of faculty discussion and approval. I really don't know the answer to that at this point.

When people apply to study at Duke, is MOOC completion a relevant factor yet, in terms of how the admissions office sizes up candidates?
It's really interesting. We aren't yet doing anything on an aggregate level. But we have been seeing home-schooled kids who took a couple of our classes online to see if they could do Duke-level work. Also, faculty who have been teaching MOOCs have reached out to their best students internationally and have encouraged them to come to Duke as graduate students. So MOOCs are entering the larger universe of recruiting modes for us.

How well can we gauge whether online students have mastered the material?
We have a pretty robust assessment process. We have staff dedicated to seeing whether students are really getting what we hope for out of the classes. I get the feeling it's going pretty well.

Online education providers are still working out their business models. What approaches seem wisest to you?
It's tough. A lot of the original motivation for MOOCs was altruistic—connecting worldwide with people who might not have access to a Duke-level education. I think a lot of faculty members are still really motivated by that. Being paid or for-profit takes that away. Charging for accreditation seems reasonable, but you almost have to have waivers equivalent to financial aid.

Have you tested out any MOOCs yourself, as a clandestine student?
I always wanted to take a good biostatistics class. I tried one, but then I realized that my college math skills had become so rusty that I would have needed to back up and do a more introductory course first. Right now, I just don't have the time. But when I retire, I'll take some.

Q&A

The Skeptic: Stanford's John Hennessy

Stanford's president questions whether online learning can match traditional instruction in motivating students.

● Stanford president John Hennessy has a background that would make it tempting to regard him as the online-education insurgents' best friend. He joined Stanford in 1977 as a professor of electrical engineering. He has founded his own computer company and continues a high-level involvement in Silicon Valley, where he serves as a Google director.

Hennessy turns out to be surprisingly cautious, though, about online education in general and massive open online courses (MOOCs) in particular. Traditional teaching has some hard-to-imitate strengths, he pointed out in an interview with *MIT Technology Review* contributing editor George Anders. Among them: classroom instructors' ability to inspire students and to gauge how well they have mastered the material.

How do you think online learning compares with traditional methods?
The advantage is the disadvantage. MOOCs let you reach a very large audience that's highly distributed in terms of its ability to master the material. That's an inherent property of a course that's meant to be massive and open. And therein lies the difficulty. If the students are all over the map, then a large fraction of them will feel everything is going too fast. Many will feel it's too slow. That's quite different from a traditional classroom at Stanford.

Two of the best-known MOOC platforms, Coursera and Udacity, were started by Stanford computer science professors in 2012. What advice did you give them?
I encouraged them to try, because I believed several things could only be learned by moving the technology out to the market quickly. First, what kind of investment would be necessary to create a high-quality platform. Second, where the market would emerge. Indeed, lots of the market turns out to involve professional training. That's outside the traditional space that universities serve. You can aim a company in that direction. It's harder for a university to move in a direction that's not coherent with its core goals and mission.

What's your perspective on blending online tools and face-to-face teaching? We're hearing a lot these days about the "flipped classroom," in which students listen to lectures online and then use class time for problem solving.
We need a lot more experiments. We need people to try out things and measure them. There's one really good experiment involving an online statistics class from Carnegie Mellon. It showed quite clearly that a flipped classroom can lead to comparable performance versus traditional instruction, in less time. If you could reduce the time that students need to learn the material—and be sure that students aren't learning less—then we would have something valuable.

Distance learning has been around for a long time. How have we moved beyond some very clunky beginnings?
Active learning. The truth is, looking at a talking video for an hour is absolutely no more motivating—perhaps even less motivating—than sitting in a large lecture hall for an hour. You need a more interactive experience that requires you to pay attention and answer a quiz before going on to the next section. That gives the students some confidence.

Professors at top-tier universities are ambitious souls. Has MOOC creation become a badge of glory in some disciplines?
For us, it's more about some contribution to the public good. I mean, there's some brand building going on, but it's mostly just a way of sharing content with people who wouldn't have access to it otherwise.

How could online learning methods become more useful?
We're trying to build analytics so that we can give feedback to faculty. In a traditional, large science or engineering class, you don't know until the midterm or the final whether there's some topic that's a disaster in terms of the students not getting it. Online, you can get feedback much sooner. You might even be able to get it before the lecture is over, so that you can fix it while the class is still going on. We'd like to fold that in, so that we can develop teaching that gets progressively better.

Can we gauge whether online students have truly mastered the material?
We're still stumbling around, finding the right mix of automated grading, peer grading, and some role for graduate students or other trained evaluators. There are just some things that can't be graded automatically. And in high-stakes situations, peer grading makes everybody nervous. Motivation and personal contact are critical issues. I just don't think that beaming a MOOC into somebody's bedroom is going to create the kind of engaging experience they're going to need to succeed in school. The technology will get better, but it will take some time.

How do you like what's in the marketplace now?
There are a wide variety of issues that have to be solved. For-profit or nonprofit; consortiums or institutions going in alone. Who actually does the instruction? Who provides the certification? They're still playing out in real time.

Did you ever try any MOOCs yourself, as a student?
I started this American poetry class from Penn. The material was well presented. For the self-motivated individual, this stuff works well. The MOOC creates a learning community that's really the modern version of a book club. I don't know how much you could charge for it—but it's an interesting learning environment.

Case Study

India Loves MOOCs

In a country of rigid teaching styles and scarce university slots, students and professors are exploring what online learning can be.

● How does a talented Indian teenager like Gaurav Goyal make his mark on the world? Ordinarily, his destiny would have been set on the morning in 2008 when he took his country's toughest college placement exam: the IIT Joint Entrance Exam. More than 300,000 students attempted the test that year; only 8,652 qualified for a spot at one of the ultra-elite Indian Institutes of Technology.

Goyal mustered a score in the top 1 percent, winning entry to IIT Delhi. But he fell just short of the cutoff for the school's most competitive degree program, the one he most wanted to pursue: computer science. Instead, Goyal was told to major in civil engineering. Other students could learn about databases. For him, hydrology awaited.

Determined to change his fate, Goyal, an extrovert with a keen interest in business, found a way to outwit the system. As he recently explained over a dinner of curried cottage-cheese skewers at a fancy lakeside restaurant in Delhi's Hauz Khas district, he wiggled his way into a variety of management courses at IIT Delhi and lined up his first job after graduation at Wipro, one of India's leading information-technology offshoring companies.

Then Goyal set out to sharpen his résumé. In early 2014, he enrolled in three online data-science classes via Coursera, all taught by Johns Hopkins professors. By earning certificates from the courses, demonstrating expertise in areas such as the programming tool R, Goyal impressed Dunnhumby, one of Britain's largest customer-analytics companies. He now works there as a Delhi-based senior analyst, using data to figure out what British shoppers want next.

Throughout India, online education is gaining favor as a career accelerator, particularly in technical fields. Indian enrollments account for about 8 percent of worldwide activity in Coursera and 12 percent in edX, the two leading providers of massive open online courses, or MOOCs. Only the United States' share is clearly higher; China's is roughly comparable. India's own top-tier technical universities have created free videotaped lectures of more than 700 courses, with the goal of putting students at regional colleges in digital contact with the country's most renowned professors.

In the United States and Europe, MOOCs have proved less revolutionary than their champions predicted when they launched on a wide scale in 2012. Rather than displacing traditional undergraduate programs, MOOCs in developed economies seem to find their biggest audience among those eager to learn more about history, psychology, or some other side interest. Those enrollees try lots of classes but often drop out after a few sessions.

It's a different story in India. There, online courses from the U.S. or Europe are finding a big following among college students and recent graduates, says Rick Levin, CEO of Coursera, which is based in Mountain View, California. They are a more serious bunch, hoping that the right technical courses can help them win better jobs. In a boon to Coursera's bottom line, emerging-market learners are also frequently willing to pay $29 to $250 for a certificate that attests to their successful performance on a final exam.

"I believe that India ultimately will be a much bigger market for MOOCs than the U.S.," says edX chief executive Anant Agarwal, who also is an MIT professor of electrical engineering and computer science. Indian students crave advanced knowledge that can open doors to a more prosperous life, Agarwal says: "If you've been trampled all your life, now you find you can stand shoulder to shoulder with the best."

Sheer demographics bolster his case: India's population of more than 1.2 billion is nearly four times the U.S. total. India's brightest students enjoy the IIT campuses' cachet as the training ground of tech-sector leaders. A handful of other state-sponsored or private universities achieve top-tier status, too. By and large, though, a degree from most of India's 35,000 colleges simply doesn't register with international employers.

EVAH FAN

For aspiring Indian engineers and scientists, online credentials offer a way to stand out from the crowd. Coursera's most popular offering in India is an intensely practical University of Maryland course on how to build mobile applications for Android devices. After that come two Python programming classes from the University of Michigan and Rice University. Next is a Stanford class on machine learning. All told, eight of Coursera's top 10 courses in India are highly technical. (Even the two nontechnical classes on Coursera's leaderboard are designed for strivers: Learning How to Learn and Introduction to Public Speaking.)

12%
Proportion of edX students based in India.

Coursera executive Kabir Chadha is trying to persuade leading Indian tech employers to embrace his company's completion certificates as an important part of their job-candidate screening. Already, companies including Google, Wipro, Infosys, Infineon, and Microsoft have hired Indian engineers with online-education credentials, though such achievements don't yet factor into recruiting standards in a consistent way, if at all. Thousands of Indian engineers now list schools such as Stanford, MIT, and Carnegie Mellon as part of their educational background on LinkedIn, based solely on completion of online courses offered by professors at those U.S. universities.

Few people have wrestled more extensively with the challenge of teaching electrical engineering to undergraduates than Anant Agarwal. A product of IIT Madras and Stanford, he has been teaching at MIT since 1988, perfecting an upbeat, high-energy classroom style that has earned him two teaching awards. With his booming voice, untucked flannel shirts, and sweeping hand gestures, Agarwal projects a geeky charisma. One of his 2007 lectures has attracted some 550,000 page views on YouTube.

Given the opportunity four years ago to a create a globally appealing online course on circuits, Agarwal could have kept the star role for himself. Instead, he reworked camera angles so that he became an unseen background voice—while circuit diagrams and problems enjoyed full prominence. Online students needed to put each lecture's concepts to work, right away, by designing their own circuits and analyzing the ways that amplifiers, inductors, and other devices would operate. Built-in software allowed students' work on a digital sketch pad to be automatically graded within seconds.

It was a most un-Indian approach, sidestepping the long lectures, rote learning, and heavy emphasis on foundational principles that typify many Indian college courses. Indian campuses and tech companies began buzzing about this rare chance to experience hands-on teaching. Circuits 6.002x, as his MOOC was called, attracted 155,000 people worldwide in its 2012 debut—nearly 50,000 from India.

"I got super-excited at the prospect of being a virtual MIT student," Shreyas Jayaprakash recently recalled. He was finishing up his undergraduate studies at a regional college in Bengaluru at the time, worried that he couldn't compete successfully against other 6.002x students from around the world. But Jayaprakash raced to complete the course quizzes within hours after they were posted. He ended up with a 99 percent score on the final exam. Today he is a design engineer for the Bengaluru office of Avago Technologies, where he inspects chips that ultimately become part of Dell, Cisco, or Facebook servers.

Taking 6.002x "improved my problem solving," says Ashwith Rego, who is pursuing a master's degree in electrical engineering from IIT Bombay. One quiz gave Rego a better understanding of oscilloscopes. Another had him analyze car suspension systems. On the hardest problems, he tapped into online discussion forums, populated by students from as far away as Argentina and Ukraine.

What Agarwal started, dozens of other U.S. professors have now exported to India, too. Jim Fowler, an assistant professor of mathematics at Ohio State, teaches Coursera's most popular online calculus class. Instead of lecturing nonstop at a whiteboard, he pauses periodically to blow up a balloon or cast shadows with a stick-figure puppet—helping learners visualize the integrals and derivatives they are being asked to calculate.

Such showmanship delighted Surya Prakash in 2013, when the West Bengal student took Fowler's calculus MOOC. Prakash had finished high school and was trying to score well enough on the Joint Entrance Exam to win admission to an elite engineering college. Earlier attempts to master calculus had gone badly, but Prakash seized on Fowler's examples and drew on them to achieve a strong test score—and a ticket to a first-tier college in Jaipur.

Mixing facts and fun in a MOOC "helps you remember things better when it comes time to take the exam," says Mahesh Kumar Hiremath, a computer science major in his senior year at BMS College of Engineering in Bengaluru, who has taken at least eight MOOCs, often to get a second perspective on his actual courses in topics such as algorithms or Java. The extra effort has paid off; Hiremath has earned As in most of his classes and is joining SAP after graduation.

In India online courses are finding a big following among college students and recent graduates, hoping that the right technical courses can help them win better jobs.

BMS's snug urban campus is a sanctuary from the noisy motorbike traffic of modern-day Bengaluru, and a contrast to the opulent 16th-century temple to the Hindi demigod Nanda that sits just across the main access road. The school attracts people with a single-minded focus on academics, many the children of middle-class accountants, engineers, and biologists.

"There are a *lot* of computer science engineers in my family," Chaitra Chandrasekhar, who's majoring in medical electronics and biomedical engineering at BMS, wryly observed, during a roundtable chat over tea and biscuits at the school. Like many of her peers, she has used online classes as a safe, easy way of expanding her horizons, even if some explorations (such as a short-lived attempt to learn German) went nowhere. Medha S. Bharadwaj, a medical electronics major, took a Python programming class to help her on the job market and a Western music class for fun.

"Every course can't be in the [U.S.-style] interactive format. Some have to be very serious lectures."

Indian technical colleges seldom offer the wide-ranging electives that can be found on U.S. campuses. So BMS students such as Sharath Chandra tend to chuckle when they admit to signing up for online oddities such as a sports management MOOC taught by the University of Pennsylvania. It's irrelevant to his computer science studies, Chandra conceded. Even so, he added, "it was fascinating to find out how Real Madrid can sign a player for $80 million, and make back $40 million of that with extra T-shirt sales."

India's vast size and rapid development mean there is always a shortage of professors. With a record 3.2 million students currently enrolled in university-level engineering programs, there aren't enough experts to teach everyone in person. Essential courses can't be offered at all in some rural colleges; elsewhere, people with just a bachelor's degree are pressed into duty as instructors for first-year courses. The best hope of fixing this predicament, says pioneering Indian computer science professor Deepak Phatak, is a much bolder role for online education.

Phatak is India's most persistent champion of tech-based ways to stretch the classroom. In 2002, he and a colleague arranged for his IIT Bombay class in information science to be live-streamed, via video, to other Indian colleges. He is an active supporter of a national program that has made stored videos of elite institutions' course lectures available free of charge to anyone who wants to watch. Recently, Phatak and three other IIT Bombay instructors teamed up with edX to offer their own online introductory course on computer programming.

Making the technology hum is the easy part, Phatak says. It's harder to rearrange university priorities so that India's best instructors can be granted enough discretionary time to build first-rate MOOCs from scratch. Another barrier, Phatak says, is schools' reluctance to provide academic credit for online learning. He has been working with the All India Council for Technical Education to establish new guidelines that would allow students to earn 15 percent of their credits online. One proposal would let outlying colleges use a blended model, in which online instruction supplements class lectures and discussions. That approach will be put into action in the 2015–16 academic years, with about 50 of India's autonomous institutes working with IIT Bombay to offer blended MOOCs in three subjects.

Eager to establish that India can create its own advanced online classes rather than importing content from the United States, the Ministry of Human Resources Development last year sketched out plans for its own MOOC platform known as Swayam. As of this June, however, only three Swayam courses had been announced. Coursera and edX each offer more than 500 online classes.

While Indian students are embracing the visual thrills and incessant mini-quizzes of U.S.-style MOOCs, their professors aren't as delighted. In 2012, Gautam Shroff, an adjunct professor at IIT Delhi, decided to create a Coursera MOOC on Web intelligence and big data. He came away with mixed impressions. Reaching a big audience was enticing, he observed, but "the average learner was nowhere near as well prepared as a typical IIT undergraduate." That forced him to teach at a more rudimentary level than he might have wanted, even though a few students were so savvy that they almost didn't need the course at all.

Shroff also found that in his field, it was hard to test the depth of students' understanding. The MOOC format required him to come up with assignments and exams that could be machine-graded, which tilted everything toward more superficial questions than might be posed in a traditional, hand-graded classroom exam.

Overall, he concluded, MOOC students are more likely to end up with an "awareness" of a field, rather than deep knowledge. That's not all bad, he observed. It just means that, at least for him, teaching a MOOC is "more like writing a short book than teaching a course."

R. K. Shevgaonkar, former director of IIT Delhi, has been testing various online education methods for at least a decade. He is confident that digital learning in some form is "a good solution" for India as it seeks to spread technical knowledge fast enough to satisfy the demands of a big, rapidly growing nation. He is eager to see India become an exporter of online academic instruction rather than a net importer from the United States.

3.2 million
Number of Indian students enrolled in university-level engineering programs

Shevgaonkar himself has posted on YouTube a massive, 60-lecture series about transmission lines and electromagnetic waves. This 2007 presentation lacks interactive quizzes or video-editing fanfare, but Shevgaonkar makes no apologies for the spartan delivery. His opening lecture has attracted a very robust 285,000 views, and a respectable 8,800 students made it to the final (60th) lecture.

"Every course can't be in the [U.S.-style] interactive format," Shevgaonkar argues. "Some have to be very serious lectures." —*George Anders*

Case Study

China's Startup Boom in Online Learning

Will a surge in distance learning for traditional subjects, test prep, language, and trade skills leave the poorest out?

● China knows a thing or two about distance learning. For two decades, the country's education ministry has used the television airwaves to broadcast agricultural lessons to more than 100 million rural students—making it the largest such program in the world. And in the early 2000s, the charitable Li Ka Shing Foundation installed satellite dishes and computers to broadcast lectures to 10,000 rural schools. Now this top-down model of online learning is being joined by a surge in new commercial and university offerings.

And it's no longer just about reaching rural provinces. In China a rapidly rising middle class—part of a population that now totals 1.4 billion—is creating a demand for education far outpacing what traditional teachers and schools can supply. In response, Chinese startups are identifying market niches and developing entirely new products, while universities are emulating online platforms first developed in the United States.

The trend is strikingly on display in Beijing's technology district, Zhongguancun, often called China's Silicon Valley, where a building housing 15 education-technology startups has become known as the MOOC Times Building. (The acronym formally means "massive open online course," but in China "MOOC" is used to describe any kind of online educational offering.) The startup community around Zhongguancun includes Hujiang, which has 80 million registered users, including three million who pay fees. Many are cramming for tests like the "gaokao," China's main college entrance exam. A startup called Jikexueyuan created a platform offering tutorials on programming and Web design that has signed up more than 800,000 users. And the newest entrants are more diverse platforms such as the parental-advice site Babytree. (Just enter Mom's due date and "you can get for you and your baby a tailored parenting guide," the site says, in Chinese.)

Chinese investment in education technologies has climbed from $137 million (in U.S. dollars) in 2013 to more than $1 billion in 2014, according to TAL Education Group, a publicly traded Chinese education firm based in Beijing.

And the startups in Zhongguancun are joined by a wide range of university and private entrants. Xuetang, a MOOC supported by Tsinghua University, for example, offers some courses on edX, an online platform sponsored by MIT and Harvard University.

Homegrown Chinese platforms for university education are emerging, too. One-Man University—founded by a former physics student at Peking University—has started distributing instructional 15-minute videos prepared by teachers to its more than 130,000 registered members through 56.com, a video-streaming website.

"There is a tremendous demand in China to get a U.S.-quality education," says Bryan Stolle, a general partner at Mohr Davidow, a venture capital firm in Menlo Park, California, that is funding Hotchalk, a company in Campbell, California, that's attempting to give U.S. universities a digital presence in China. Each year 750,000 Chinese students apply for college in the United States, and fewer than 200,000 are accepted, he says.

There are some concerns accompanying this trend. Although China has by far the world's largest number of Internet users, with more than 640 million people online, Internet penetration is only about 46 percent, compared with 87 percent in the United States. And a number of studies suggest that the benefits of online education accrue mostly to the already advantaged. Justin Reich, executive director of the PK12 Initiative at MIT and a research scientist in MIT's Office of Digital Learning, who recently spent time touring startups at the MOOC Times Building and talking to educators in China, says he also heard concerns about students becoming isolated and losing out on useful peer pressure, but that he generally encountered great enthusiasm.

"In China, all of these concerns are voiced against the backdrop of a much larger concern that there is a tremendous unmet demand for education," he says.

Online courses can in some cases not only fill a brick-and-mortar void but actually do a better job at teaching certain specific skills, says Rong Wang, a professor at Peking University who researches education finance. Traditional schools are very exam-oriented, "and many teachers don't have adequate capacities in delivering practical skills instruction to students," she says. And working adults aren't being served by traditional schools, which generally have only limited classes on evenings and weekends, she says.

Reich adds that there has been some discussion within the government of defining a set of requirements for degrees and then letting students meet some of them through MOOCs. If the government were to allow MOOC credits to apply toward a degree, he points out, such a scheme could rapidly be implemented nationwide. *—David Talbot*

ACCESS THE FULL REPORT ONLINE

Read more about the technologies and innovators changing the way we learn.

Los Angeles's Troubled Tech

Open-Access Instruction

Q&A: Sebastian Thrun

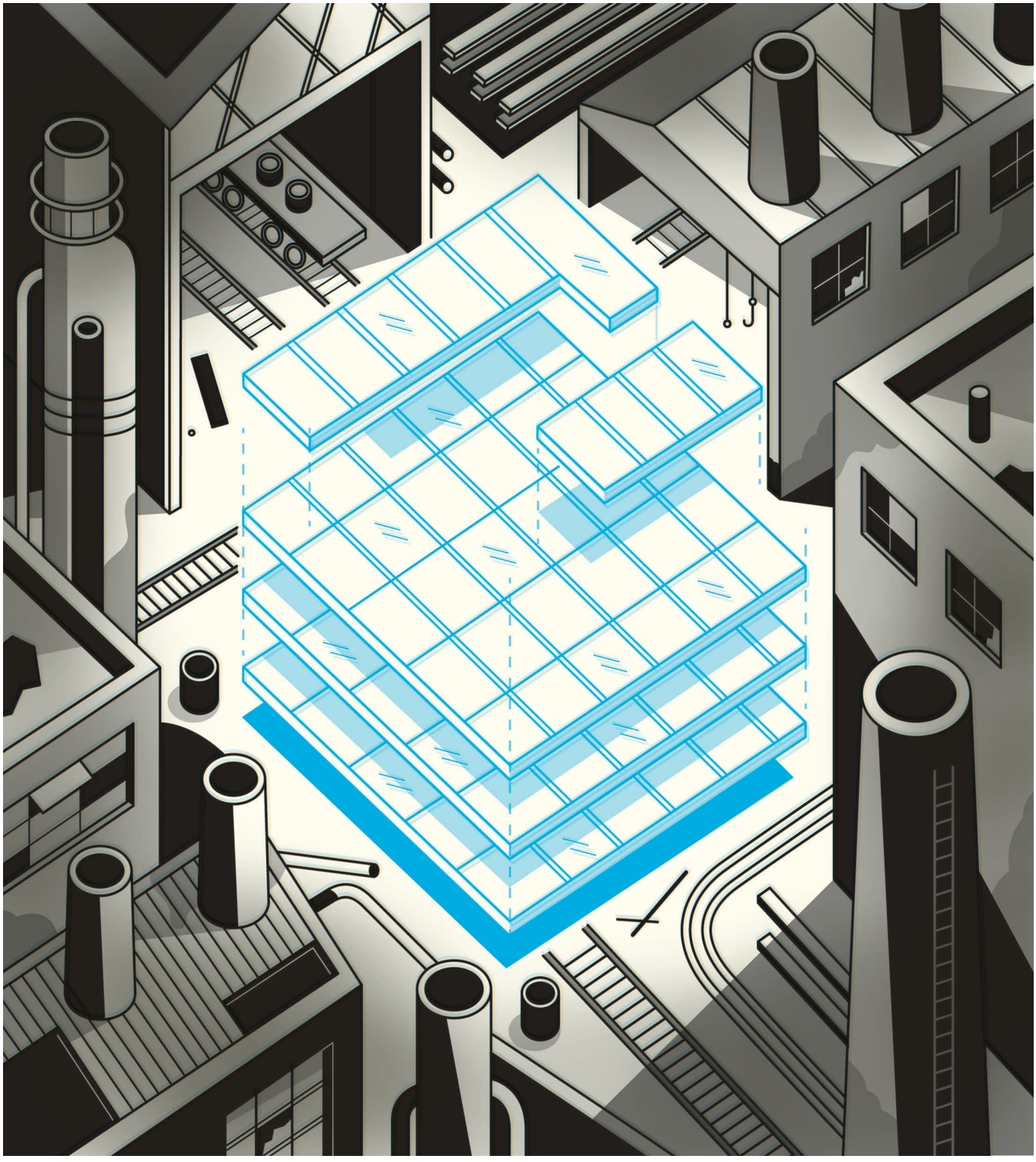
Duolingo and Fluency

Student Privacy

Best Tech for Teachers

Top MOOCs

technologyreview.com/business



HARRY CAMPBELL

Reviews

Paying for Solar Power

SolarCity's massive new manufacturing plant in Buffalo, New York, reflects a booming demand for solar power. Is it sustainable?

By David Rotman

The rail cars that once carried iron ore around Republic Steel's sprawling plant at the edge of downtown Buffalo, New York, were plowed under when the steel company abandoned the location in 1984. They were recently discovered when excavation began for the so-called gigafactory to be operated by SolarCity, the country's leading supplier of solar panels. Now the rusted cars and a scattering of other relics from the days of Republic Steel greet visitors to the construction site, a reminder of the city's past manufacturing might and a testament to the dream that North America's largest solar-panel manufacturing facility can help revive it.

Buffalo is attempting an economic comeback fueled by the state's Buffalo Billion initiative, a multi-year redevelopment plan spearheaded by Governor Andrew Cuomo. Included in the funding is support for a new genomic research center and an information technology center, but at the heart of the city's ambitions is the solar factory, which New York is spending $750 million to build and equip. SolarCity, based in Silicon Valley, will lease it, essentially for free, and has committed to spending $5 billion on its Buffalo operations over the next decade. For Buffalo, it's an attempt to reimagine its future around solar manufacturing. For SolarCity, it will solidify its position as one of the country's most aggressive and fastest-growing solar companies.

The plan to build the massive manufacturing facility comes at a time when demand for solar power is booming in the United States. In 2008, the nation had about 1.1 gigawatts of photovoltaic power, the dominant type of solar energy; by the end of 2014 it had 18.3 gigawatts. Last year, homeowners, businesses, and energy companies added about 6.2 gigawatts, and they are expected to install another eight gigawatts this year. Much of that is in California, but solar power is taking hold in other states, boosted by a mix of federal tax credits and state and local incentives. Roughly a third of the electricity generation capacity added last year in the United States was solar, second only to natural-gas plants. (Even so, solar power still provides less than 1 percent of the country's electricity.)

SolarCity "gigafactory"
Buffalo, New York

"The Future of Solar Energy"
MIT Energy Initiative, May 2015
https://mitei.mit.edu/futureofsolar

SolarCity has played a large part in the rapid expansion. By offering innovative financing schemes, it has spurred strong demand for rooftop panels on homes, the fastest-growing sector of the solar market. Instead of buying the expensive solar panels and paying for their installation, homeowners participating in one of SolarCity's offerings can lease the system for 20 years, paying a monthly fee. Because it owns the panels, SolarCity benefits from the generous 30 percent federal investment tax credit for solar power; the homeowner is credited at retail electricity rates for any surplus power fed back to the grid. SolarCity is still unprofitable, but its revenue doubled from 2012 to 2014 as its leasing program proved attractive for homeowners—especially in locations with high electricity rates and lots of sunshine, such as California. The company expects to install enough panels this year to produce a gigawatt of power.

Not coincidentally, a gigawatt will be the capacity of the Buffalo factory when it is fully up and running, which is scheduled for the beginning of 2017. Until now,

the company's business has been built around marketing, financing, and installing solar systems. Instead of producing solar panels, it buys them, mostly from Chinese manufacturers. The Buffalo factory changes all that. "Our aspiration is to build many more of these factories over time," says Peter Rive, the chief technology officer, who founded SolarCity with his brother nine years ago (their cousin Elon Musk is the company's chairman). And though Rive says the company doesn't want to "take its eye off the ball" in getting the Buffalo plant built and operating, he adds that shortly after that's accomplished, "we want to create the largest solar facility in the world, never mind the Western Hemisphere." Indeed, SolarCity stated earlier that its plan is to add "one or more significantly larger plants" with annual production capacity an order of magnitude greater than that of the Buffalo facility.

SolarCity's factory in Buffalo, seen here in May, is due to be completed next year.

The company will make a new type of photovoltaic technology in Buffalo. The solar cells use crystalline silicon—the material used in conventional cells—with a thin film of another form of silicon and a layer of a semiconductor oxide. The hybrid solar-cell design, which SolarCity got when it bought a small company called Silevo in 2014, is designed to be more efficient than standard silicon cells in converting sunlight to electricity, as well as relatively cheap to make. But while SolarCity operates a 32-megawatt plant in Hangzhou, China, that Silevo built to make the solar cells, quickly scaling up those operations to the far larger plant in Buffalo will be an engineering feat.

Even if all goes well, the gigafactory could be facing a dramatically different solar-power market. At the end of 2016, the federal tax credit for solar power is due to drop from 30 percent to 10 percent for businesses and to disappear altogether for consumers who buy their own solar panels. By making residential solar power less affordable, the change could be devastating to the industry. And it will come just as the Buffalo factory is ramping up its manufacturing capacity.

True costs

Fears about what will happen when the tax breaks decrease are fueled by an unfortunate reality: in most locations and under most conditions, unsubsidized solar power is still far too expensive to compete with other sources of electricity. And rooftop solar is especially expensive. Subsidies and other government incentives are the reason the solar market is booming. If technologies were chosen purely on the basis of what it costs to produce power, "there isn't a market for residential solar," says Severin Borenstein, a professor at the Haas School of Business at the University of California, Berkeley, and an expert on electricity economics. Without government incentives for clean energy like solar, he says, "natural gas wipes everything else away."

Much has been made of the fact that solar power is nearing grid parity—the point at which it is just as cheap as electricity from natural gas or coal. Most recently, a report by Deutsche Bank calculated that solar power is already at grid parity in 14 U.S. states and that nearly all the others will be there by next year. But that doesn't mean it is just as cheap to produce solar power as it is to generate electricity with natural gas. The Deutsche Bank report compares today's cost of solar power with the retail price of electricity, which includes various charges, includ-

BRENDAN BANNON

ing fees for upgrading and maintaining the grid. That's a sensible comparison for consumers deciding whether to install solar power. But it isn't a true comparison of the costs to actually produce electricity. And *that* is the comparison that matters in determining the most cost-effective way to introduce more clean power and lower our carbon emissions.

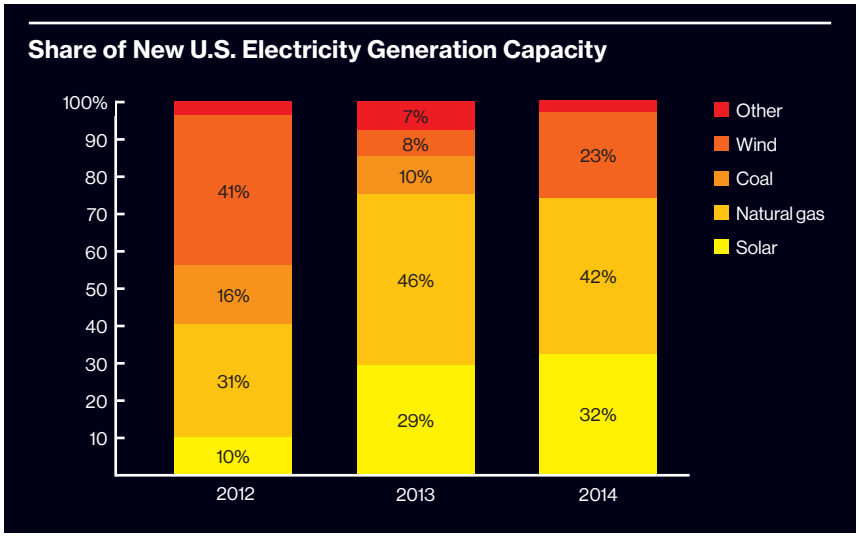
The cost of the photovoltaic module—the chunk of silicon or other semiconductors that convert sunlight to electricity—has dropped impressively over the years. A silicon solar module sold for $4 per watt in 2008; in 2014 it was 65 cents per watt. But it has been more difficult to cut the other expenses—the so-called balance of system (BOS) costs, which include hardware like the inverters that are necessary to connect the panels to the grid and, most crucially, the labor to install the equipment. Installing heavy solar panels on the roofs of houses is particularly expensive. In such installations the BOS costs account for roughly 85 percent of the total expense of the system, according to a lengthy MIT report called "The Future of Solar Energy," released in May. Or as Robert C. Armstrong, director of the MIT Energy Initiative and one of the authors of the report, puts it: "Even if you give away the [photovoltaic] materials for free, you still couldn't produce electricity as cheaply as with coal or natural gas."

Take away the tax credit and residential solar power will remain far above grid parity in all states for years to come.

Economists favor a measurement called "levelized cost of energy" to compare different sources of electricity. The calculation estimates the expense of installing a system and the average cost of producing electricity over its lifetime. When expenses are computed this way, big solar farms that directly supply electricity to utilities are the most cost-effective kind of solar power. According to the MIT report, solar-power plants in Southern California and Massachusetts would have levelized costs of 10.5 cents and 15.8 cents per kilowatt-hour, respectively (California gets far more sun, producing greater output). Meanwhile, a new natural-gas power plant can generate power at 6.6 cents per kilowatt-hour. The comparison for residential solar is even more discouraging: a Massachusetts home generates solar power at 28.7 cents per kilowatt-hour, and one in Southern California produces it at 19.2 cents, says the MIT report.

That is without government subsidies. With today's incentives, including the tax credit, the numbers become far more favorable for solar power, even though it is still generally more expensive than producing power with gas-fired plants.

Stefan Reichelstein, a professor at Stanford University's business school and director of the Steyer-Taylor Center for Energy Policy and Finance, and his colleagues have looked at how changing the tax credit in particular will affect solar economics. They found that even without the tax credit, large solar farms could be competitive with natural-gas plants by 2025 in states like California. But the story is very different for residential power. With a 30 percent credit, a residential solar installation produces power at less than the price of retail electricity in California (the state's electricity rates are far higher than the national average). The same is true in other sunny states like Colorado and North Carolina, though not in a state like New Jersey. But drop the credit to 10 percent and no state is at grid parity. Take away the tax credit completely and—even assuming a continuing decrease in the cost of solar cells and installation—residential



solar power remains far above grid parity in all states for many years to come.

No snow days

We will probably need vast amounts of solar power if we're going to avoid the more dire effects of climate change. MIT's Armstrong, for one, calculates that roughly 50 percent of the world's electricity will need to come from solar power by 2050, requiring about 12.5 terawatts of photovoltaic capacity. We've barely begun the difficult and expensive transformation. Eventually, it will take vastly improved solar materials and better storage options such as batteries, as well as a realistic price on carbon emissions. But meanwhile, we need policies that are more effective in helping to make solar power a significant contributor to our electricity supply. As Armstrong says, "Money is not infinite. We need to get as much solar as we can for the money."

The reality that the boom in solar power has depended on government subsidies doesn't mean such incentives should end. To the contrary, it makes it obvious just how important they are to achieving the goal that society cares about: an overall reduction of carbon dioxide emissions at the lowest possible cost. But they must be carefully designed to be as fair as possible. This means, says Borenstein, that subsidies should not favor inefficient versions of clean-energy technologies, such as rooftop solar over utility-scale plants. "We need to take our thumb off the scale," he says.

A broader danger is that incentives for solar in general will increasingly be perceived as unfair or too costly.

Take the practice of net metering, the policy in most states that effectively allows residents to sell solar power back to the grid at retail electricity prices. Nearly all homes with rooftop solar are connected to the grid, a necessity given the intermittent nature of solar power. These homeowners are essentially using the grid for power storage and backup, and they reap a small windfall from the high retail price of electricity in many states, including California and New York. Advocates for solar power argue that these installations add power to the grid, help offset demand during the day, and provide other benefits that stabilize the grid. Still, says Borenstein, net metering is clearly a subsidy that favors those with residential solar and adds costs to operating the grid—expenses paid for by other users.

The result has been a contentious debate in many communities and states over setting limits on the amount of solar power that qualifies for net metering. A broader danger is that incentives for solar power in general will increasingly be perceived as unfair or too costly at a time when it is clearly not yet ready to compete without subsidies. Even those who criticize the hodgepodge of existing state and federal incentives for solar, such as Borenstein and Armstrong, aren't eager to see the tax credit suddenly change next year. "Turning off the credit abruptly could damage the [solar] industry," says Armstrong. "And that would be a shame."

Indeed, the change in tax policy will be a critical test of just how reliant the solar industry is on subsidies. SolarCity's Rive believes it will cause the market to "stagnate for a couple of years." He acknowledges that SolarCity will no longer be able to compete in several states that have low electricity rates. But he predicts his company will "be okay" given its relatively low-cost products. And he suggests that the Buffalo gigafactory could provide a strong competitive advantage.

SolarCity expects the solar panels built at the factory to be able to convert 22 to 23 percent of the sunlight that hits them into electricity, compared with about 15 to 16 percent for conventional silicon technology. That means homeowners could install fewer panels to produce the same amount of power, or they could install the same number of panels and produce more power. Either way, it could help keep the company competitive.

DATA FROM SOLAR ENERGY INDUSTRIES ASSOCIATION AND GTM RESEARCH

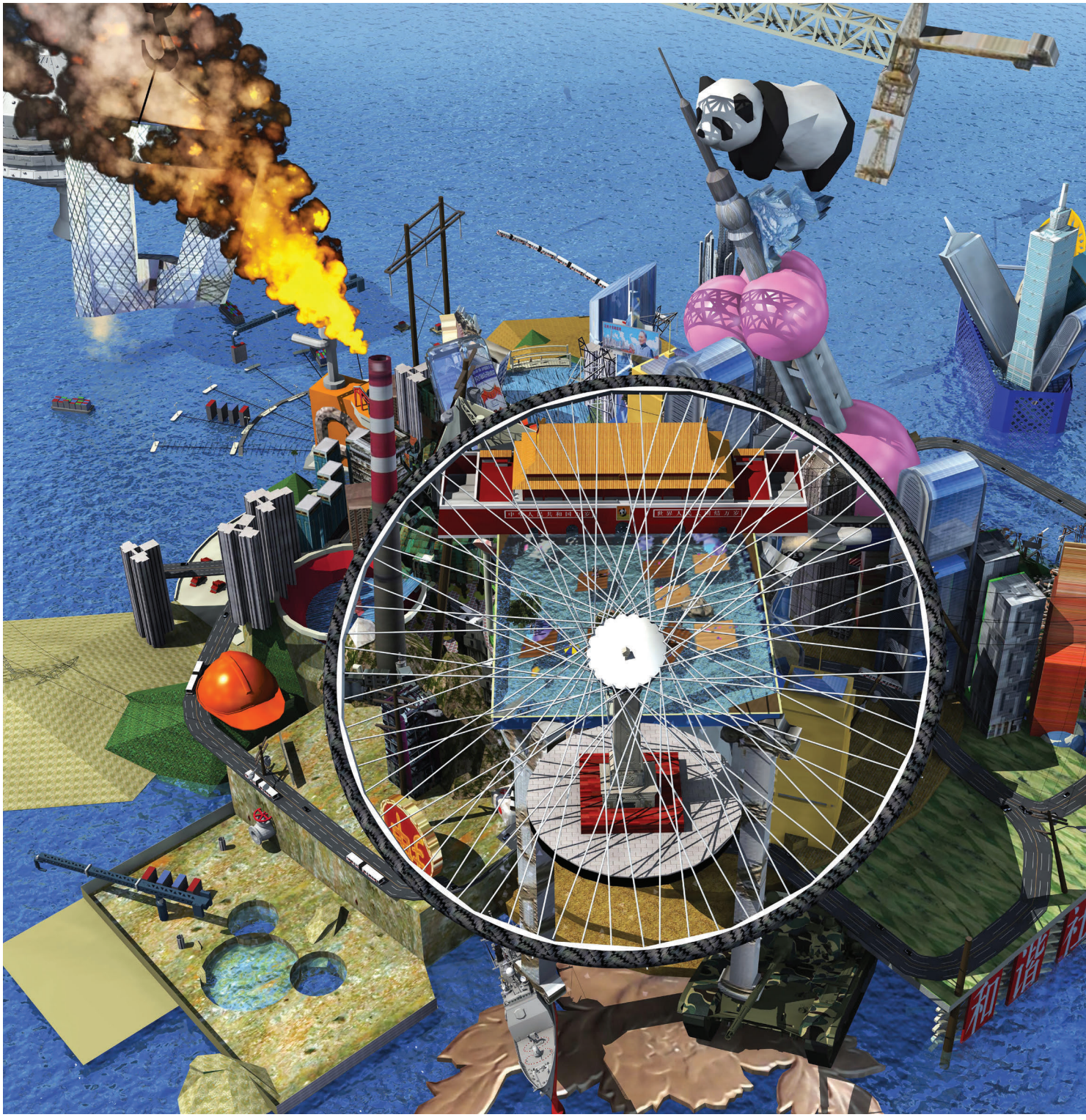
The new technology could be a very big deal for Buffalo, too. Overall, the gigafactory is expected to create 3,000 jobs in the city, half in the factory and another 1,500 with contractors and suppliers. SolarCity has also committed to employing 2,000 workers in the state over the next five years in sales and installation of its solar panels. It's not exactly re-creating the jobs of the steel industry that once dominated the area, but it's a start. (When Republic Steel closed in 1984, it had 2,500 workers, though Bethlehem Steel a few miles away in Lackawanna had far more.)

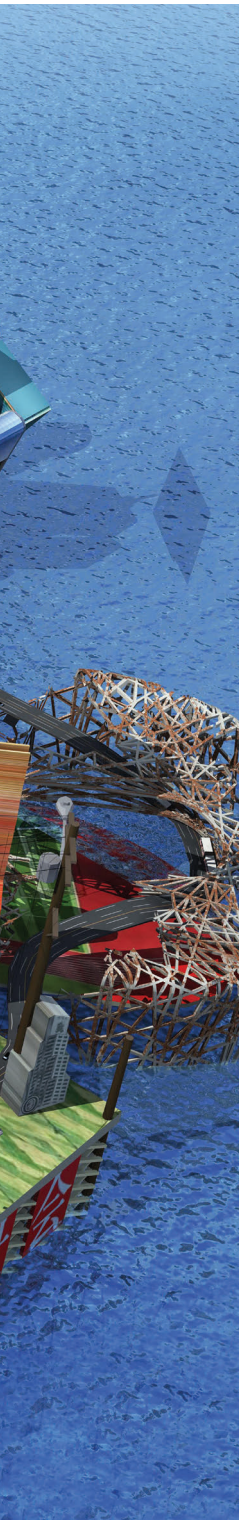
As one of the cloudiest cities in the United States, Buffalo is not a particularly attractive area for solar power. Rather, SolarCity is making its manufacturing debut there because of the state's generous incentives and the city's industrial infrastructure and experience. Ironically, Buffalo offers another huge benefit: the electricity rate for manufacturers averages just 4.79 cents per kilowatt-hour, which is possible because of cheap hydroelectric power generated from Niagara Falls. If the company wants to make the transition from being essentially a solar-services company to a manufacturer playing an important role in the country's economy, Buffalo is a good place to be.

Earlier this summer, hundreds of people in the local business community packed a downtown hotel to hear SolarCity describe its plans and learn about opportunities to supply services to the gigafactory. It was the first formal meeting between executives from SolarCity, with their Silicon Valley enthusiasm and unbounded ambition, and many of the business leaders in a factory town that has suffered through decades of economic disappointments. SolarCity will produce 10,000 panels a day at the factory, one of its executive told the audience, and "bringing it down due to weather is not an option." (No doubt the assertion made many remember that seven months earlier seven feet of snow had fallen over a few days, paralyzing the city.)

Buffalo, once the eighth-largest city in the United States, prides itself on a recent economic renaissance. The downtown and a renovated waterfront are bustling with activity and dotted with construction projects. But this renewal is heavily supported by the state's investments. And the success of SolarCity, itself a huge recipient of the state's funding, could be critical in determining the city's economic future. It will also be a defining test for the role government incentives will play in further driving the expansion of solar power.

David Rotman is the editor of MIT Technology Review.





COURTESY OF CAO FEI AND VITAMIN CREATIVE SPACE

Motion Pictures

Technology is now allowing artists to do something they've aspired to since the stone age: make their paintings move.

By Martin Gayford

Promenade
By Julian Opie (2012)

Pauvre Pierrot
By Charles-Émile Reynaud (1892)

Film No. 3: Interwoven
By Harry Everett Smith (1947–49)

Nine Drawings for Projection
By William Kentridge (1989–2003)

Felix in Exile
By William Kentridge (1994)

Headless Drummer
By David Shrigley (2012)

A View from the Other Side
By IC-98 (2011)

Tiger Licking Girl's Butt
By Nathalie Djurberg (2004)

Cat
By Bu Hua (2002)

RMB City
By Cao Fei (2008)

David
By Sam Taylor-Wood (2004)

Dame Zaha Mohammad Hadid
By Michael Craig-Martin (2008)

Computer Portrait of Laura Burlington
By Michael Craig-Martin (2010)

"By and large, visual art has always been defined as static," the abstract artist Frank Stella observed to me in 1998, "but the tradition has always been to use illusion to create a sense of motion." He was quite correct, historically speaking. From the days of the cave artists of the Cro-Magnon era, tens of thousands of years ago, artists have attempted to make images of a world that is constantly rushing, drifting, rippling, and shifting. Or as Stella put it: "If something moves, that's how you can tell it's alive."

Many of the most memorable images in the canon are of figures and animals in motion: the *Victory of Samothrace* from around 190 BCE, her drapery fluttering with the rapidity of flight; Titian's *Bacchus* of 1520–23, depicted in midair leaping from his chariot toward Ariadne; Marcel Duchamp's *Nude Descending a Staircase (No. 2)* (1912), like a multiple-exposure photograph of naked woman walking. But even as Stella spoke, changes in technology were giving artists the opportunity to do something more: to make not just pictures that appeared to move but images that actually did. Increasingly, over the last decade and a half, they have been exploring and exploiting animation—that is, making drawings and paintings that move.

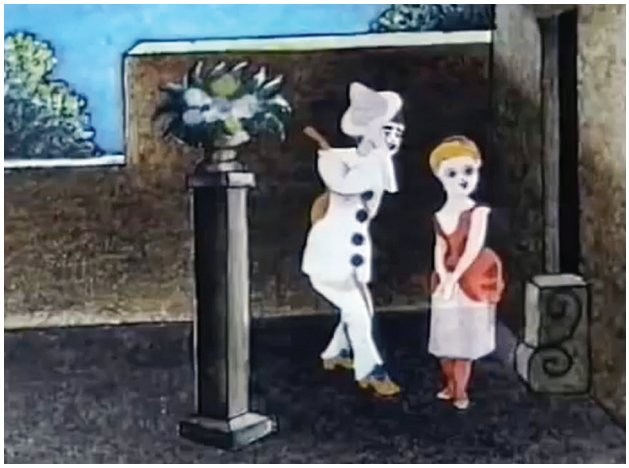
To see an example, go to Calgary, where a 24-foot tower stands on a site near East Village. On four specially constructed LED screens mounted on its sides, six figures constantly pace and saunter, drawn in a style of bold but precise simplification, so while a head may be merely a circle, their garments bunch and bag in a distinctively naturalistic fashion. Round and round they go, bunching up and separating, each with an individual gait: an updated version of the running figures on a Greek vase.

This is *Promenade* (2012) by the British artist Julian Opie, and the methods he used to make it involved interplay between digital technology, photographic media, and graphic invention. He first filmed individuals and then drew over the resulting images on a computer, reducing them to spare, essential outlines.

The avant-garde art world was slow to take up animation—about a century late, to be precise. The first public showing of an animated cartoon—*Pauvre Pierrot* by Charles-Émile Reynaud, presented in Paris in 1892—actually predated the initial such screening of a movie (by the Lumière brothers, in 1895). There were reasons, however, both practical and psychological, why highbrow artists didn't take easily to Looney Tunes.

Animation was very big business, and a more significant medium than conventional histories of film allow. The biggest movie stars of the 1930s—or so the painter David Hockney has argued—were not Clark Gable and Greta Garbo but Mickey Mouse and Donald Duck. But to work like Disney required huge resources: teams of draftsmen at drawing boards, a mighty studio. And the results were the epitome of what the highbrows of the mid-20th century were encouraged to despise.

RMB City, by Cao Fei, exists only in the online virtual world Second Life.



Top: Pauvre Pierrot *(1892). Middle:* Felix in Exile *(1994). Bottom:* Tiger Licking Girl's Butt *(2004).*

One of the most influential utterances of that period was the essay "Avant-Garde and Kitsch" (1939), by the critic Clement Greenberg. In that dichotomy, high art was Braque, Miro, Mondrian, Kandinsky, Brancusi, Klee, Matisse, and Cezanne. Disney was self-evidently kitsch (even if he may be retrospectively hailed as an important artist). Therefore, if artists of that time dabbled in animation—as the eclectic Beat Generation figure Harry Everett Smith (1923–91) did—the results were likely to be both low in production values and nonfigurative in imagery. Smith's pioneering *Film No. 3: Interwoven* (1947–49), for example, is a flickering sequence of bobbing colored squares and rectangles. Not Tom and Jerry but a mobile Mondrian.

What artists, critics, and audiences alike have to decide is whether and when the blunt reality of animated motion is an improvement over the illusion.

The low-tech quality persists in the work of the South African artist William Kentridge (born 1955), who has built a huge reputation largely by making animated films. It was the series he titled *Nine Drawings for Projection* (1989–2003) that really caught the attention of the international art world. The works, which are concerned with the struggle for freedom in the Apartheid era, feature two recurring characters, Soho Eckstein and Felix Teitlebaum.

Kentridge's term for what he does is significant—not cartoons, or even animated films, but "projected drawings." His technique is idiosyncratic, even primitive. Each film consists of changes made to a single sheet of paper, which is drawn on in charcoal with a limited amount of color applied in pastel. He erases part of the image and redraws to create each change and movement, then takes some 35-millimeter frames of the image and alters it again. The result, which often contains ghostly traces of imperfectly erased lines (Kentridge has explained this is simply because he "could never make a perfect erasure"), has a haunting quality. The effect of a work such as his *Felix in Exile* (1994) is not so much of an animated film as of a drawing come to life: not slick and professional, but stark and sincere, which perfectly fits the subject.

This kind of consciously hand-drawn look continues to have its appeal to artists making animations. David Shrigley's short digital animations, such as *Headless Drummer* (2012), have a minimalist style somewhere between cartoon and graffiti, with a surreal edge. (Why does his manically rhythmic percussionist not have a head?)

Drawing remains the starting point of the art duo calling itself "IC-98." IC-98 is based in Turku, Finland, and is made up of Visa Suonpää and Patrik Söderlund, who represented their country at

the 2015 Venice Biennale. Their animations start with collage and those venerable graphic tools, paper and pencil.

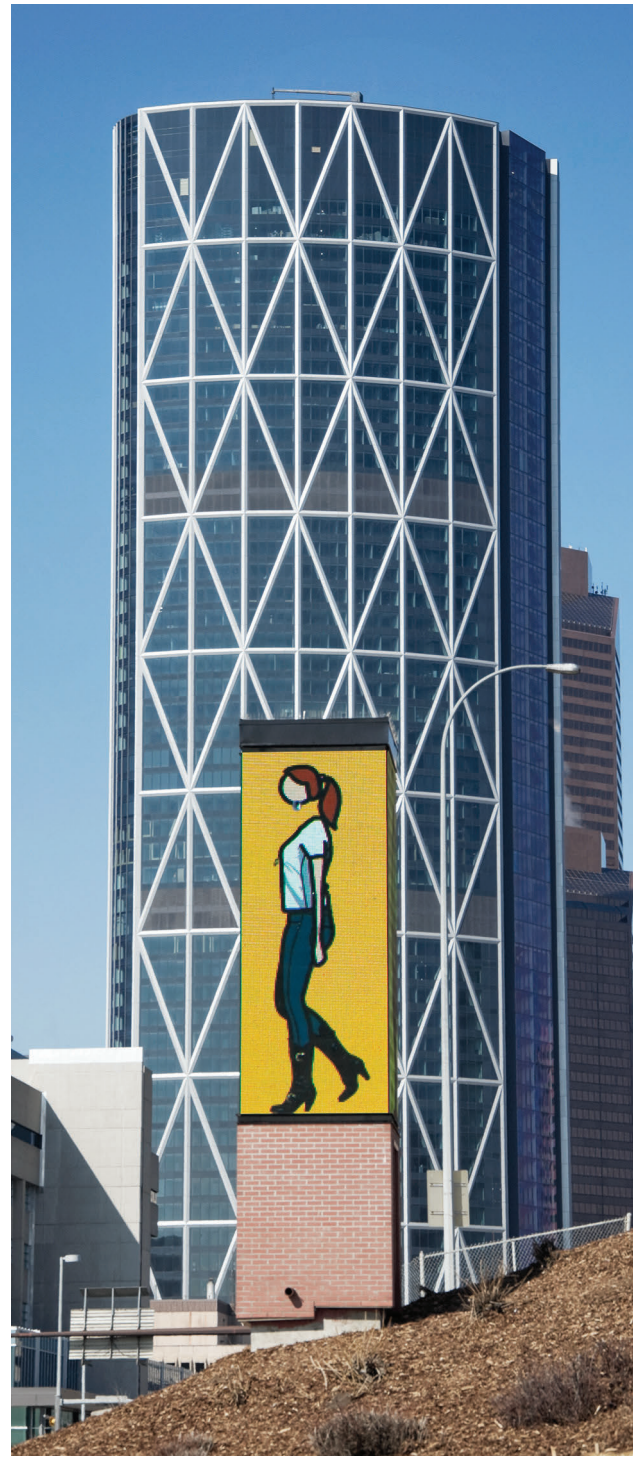
The image then undergoes manipulation in Photoshop; a professional animator, using digital tools, adds additional effects. The result is fundamentally a landscape drawing that changes very slowly, sometimes almost imperceptibly, as nature does. Over the hour and 10 minutes of *A View from the Other Side* (2011), the constant view is of a classical portico. As we watch it, seasons come and go, leaves grow and fall, until eventually the structure falls into ruin. This is animation on the time scale of history and ecology.

Another younger artist who has recently risen to prominence using a homemade-looking variety of animation is the Swedish Nathalie Djurberg (born 1978). Her most distinctive works use the technique known as clay animation, or "claymation," in which malleable sculptures made of a material such as Plasticine are altered between frames to create the effect of movement. This medium—used to great effect by Nick Park in movies such as *Chicken Run* (2000)—is not quite as old as drawn stop-motion animation, but it dates back to 1908. Djurberg's innovation is not technical; indeed, her moving images—like Kentridge's—have a jerky, unpolished quality. The novelty lies in the bizarre and erotic quality of her subject matter: a hugely overweight woman giving birth to a rhinoceros, for example, or the self-explanatory *Tiger Licking Girl's Butt* (2004).

Since the millennium many artists have embraced newer technology not only to make but also to distribute their work. From the late 1990s, software such as Adobe Flash made it relatively easy to be your own Disney—or, at least, your own Kentridge. A number of young painters, especially in the Far East, used such tools to make animated films and posted them to the Web so that a large audience could enjoy them. One of the first of these was Bu Hua (born 1973). Trained as a painter and based in Beijing, she rapidly created a series of short films in 2002, including *Cat*.

In aesthetic terms *Cat* retains a freehand expressive line that looks close to Kentridge's, and the story about a wandering, homeless, unfortunate feline parent and kitten has a touching—or, according to taste, cloying—emotional quality. It has been viewed 633,451 times on the website Flashempire.com, a number that would be extremely impressive for a major museum exhibition and is unprecedented for a youthful and little-known artist (although, of course, quite normal for a viral Web hit).

In 2008 another Chinese artist, Cao Fei (born 1978), created a work of art in the form not of an animated film but of an interactive, computer-generated environment: RMB City, which exists in Linden Lab's online virtual world, Second Life. This is both a work of art and a platform on which further works can be staged, among them film and photography exhibits by Cao,



COURTESY OF JULIAN OPIE

Promenade *(2012), by Julian Opie, in Calgary, Alberta. Opie films people and then draws over the resulting images on a computer.*

featuring her virtual avatar, China Tracy. *People's Limbo* and *Fashions of China Tracy* (both 2009) are two examples.

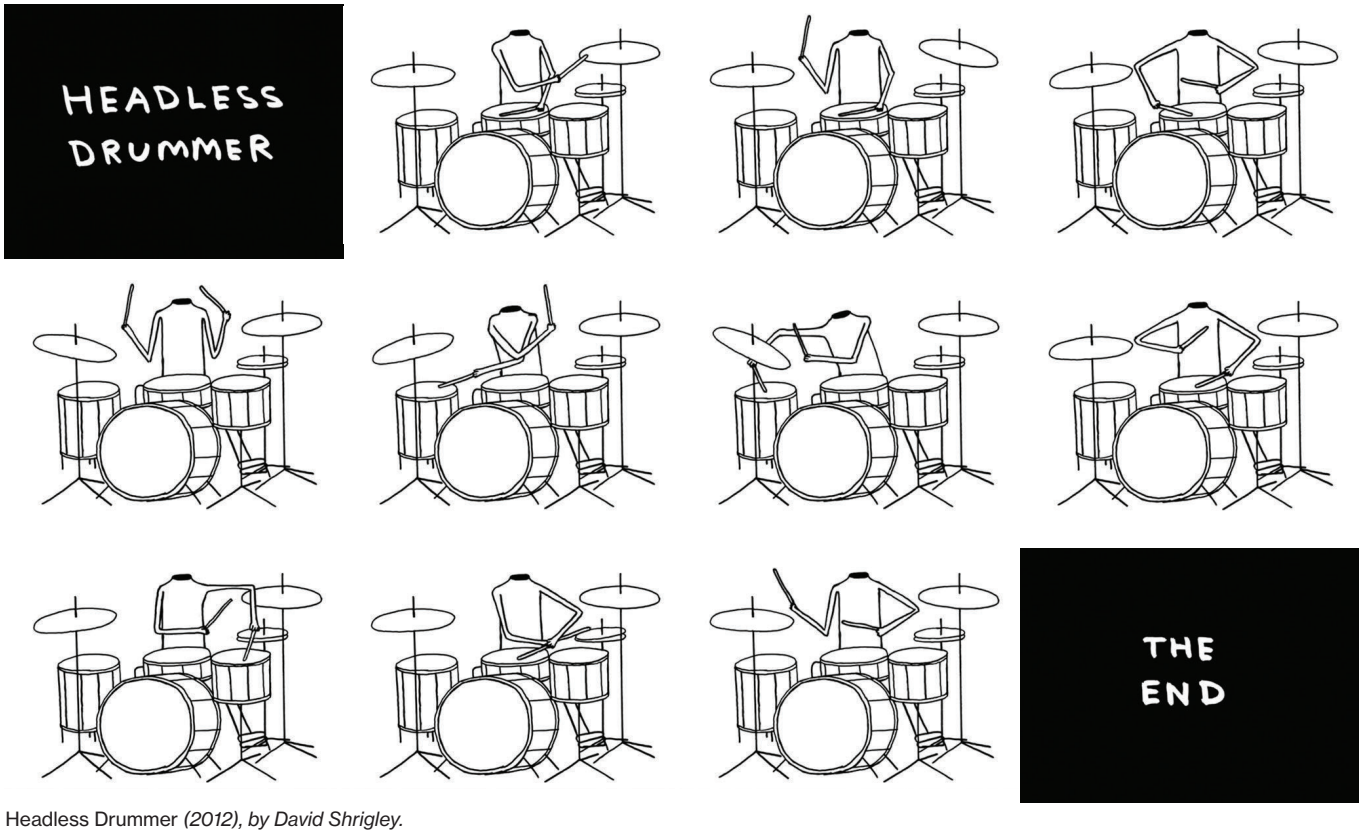
RMB City has the look and characteristics of a massively multiplayer online role-playing game (or MMORPG), but no game is involved. Instead, it is a landscape parallel to the rapidly expanding China of the early 21st century, in which a grand hall from the Forbidden City coexists with a version of Herzog and de Meuron's stadium for the Beijing Olympics, facilities for teleportation, high-rise blocks, and elevated highways.

It is very much of its time. As Brian Droitcour noted in *Art Forum*, few works got as much attention in 2008, let alone works in construction (the making of RMB City was constantly on view in London's Serpentine Gallery). The passage of half a decade has given it a period look. Game technology has moved on, producing ever greater verisimilitude.

All works of art contain clues to the date of their creation. But there are specific problems for artists using software created for film animation or digital games. In a few decades, no one may be able to access the software, and there are other difficulties that oil paint does not present. As Julian Opie has remarked, "It is an incredible headache to try and figure out technology, and it moves so fast that by the time we figure the whole thing out, quite often we find that that technology has been discontinued."

Nonetheless, he and other artists are using technology—new and not so cutting-edge—to create works that their predecessors could only imagine. On the walls of Hogwarts School of Witchcraft and Wizardry in the Harry Potter novels are highly unusual portraits; the people in them stir in their frames and speak. Such moving portraits are not pure fantasy. We have video images of sitters, such as Sam Taylor-Wood's *David* (2004), a 67-minute chronicle of the footballer David Beckham sleeping. There are also animated, drawn portraits. Opie has made a number, including *Elena*, *Sissi*, *George*, and *Jack* (all 2014)—continuous computer animations on LCD screens, who turn their heads and blink.

The British painter Michael Craig-Martin has also employed digital technology to animate his pictures, but in a



Headless Drummer *(2012), by David Shrigley.*

COURTESY OF DAVID SHRIGLEY, STEPHEN FRIEDMAN GALLERY (LONDON), ANTON KERN GALLERY (NEW YORK), YVON LAMBERT (PARIS), GALERIE FRANCESCA PIA (ZURICH), BQ (BERLIN), AND GALLERI NICOLAI WALLNER (COPENHAGEN)

different manner: in his work, the transformations are not linear but chromatic.

Craig-Martin made a portrait of the architect Dame Zaha Mohammad Hadid in this idiom for the National Portrait Gallery in London in 2008. The lines of the portrait never alter. But the colors constantly change in a varied, randomized fashion controlled by software. The potential color combinations are very numerous. His *Computer Portrait of Laura Burlington* (2010) divides the sitter's face into nine sections—hair, lips, skin, etc.—that slowly run though permutations of 44 shades of color selected by the artist. The sitter is married to the heir to the Duke of Devonshire, and the picture now hangs at Chatsworth House, the Duke's country house, among the earlier portraits by Reynolds and Gainsborough.

In 1962, David Hockney painted a picture of two men menaced by a huge leaping leopard. In tiny letters he wrote a reassuring message on the canvas: "They are perfectly safe this is a still." But more and more, what matters in art is not creating images that appear to move—as has been the case since the days of the cave paintings at Lascaux—but creating images that actually move. What artists, critics, and audiences alike have to decide is whether and when that blunt reality is an improvement over the illusion. The aurochs, stags, and horses on the walls at Lascaux were painted to be seen in the flickering torchlight, and would have shimmered with apparent movement. Yet because they are frozen in a moment, each animal still possesses a specificity, a quality of being *captured*, that animation may find difficult to replicate.

Martin Gayford's latest book is Rendezvous with Art, *written with Philippe de Montebello. His last story for* MIT Technology Review *was "Enlightened Spaces" (May/June 2014).*

ROBERT RISKO

Tech's Enduring Great-Man Myth

The idea that particular individuals drive history has long been discredited. Yet it persists in the tech industry, obscuring some of the fundamental factors in innovation.

By Amanda Schaffer

Since Steve Jobs's death, in 2011, Elon Musk has emerged as the leading celebrity of Silicon Valley. Musk is the CEO of Tesla Motors, which produces electric cars; the CEO of SpaceX, which makes rockets; and the chairman of SolarCity, which provides solar power systems. A self-made billionaire, programmer, and engineer—as well as the inspiration for Robert Downey Jr.'s Tony Stark in the Iron Man movies—he has been on the cover of *Fortune* and *Time*. In 2013, he was first on the *Atlantic's* list of "today's greatest inventors," nominated by leaders at Yahoo, Oracle, and Google. To believers, Musk is steering the history of technology. As one profile described his mystique, his "brilliance, his vision, and the breadth of his ambition make him the one-man embodiment of the future."

Musk's companies have the potential to change their sectors in fundamental ways. Still, the stories around these advances—and around Musk's role, in particular—can feel strangely outmoded.

The idea of "great men" as engines of change grew popular in the 19th century. In 1840, the Scottish philosopher Thomas Carlyle wrote that "the history of what man has accomplished in this world is at bottom the history of the Great Men who have worked here." It wasn't long, however, before critics questioned this one-dimensional view, arguing that historical change is driven by a complex mix of trends and not by any one person's achievements. "All of those changes of which he is the proximate initiator have their chief causes in the generations he descended from," Herbert Spencer wrote in 1873. And today, most historians of science and technology do not believe that major innovation is driven by "a lone inventor who relies only on his own imagination, drive, and intellect," says Daniel Kevles, a historian at Yale. Scholars are "eager to identify and give due credit to significant people but also recognize that

they are operating in a context which enables the work." In other words, great leaders rely on the resources and opportunities available to them, which means they do not shape history as much as they are molded by the moments in which they live.

Musk's success would not have been possible without, among other things, government funding for basic research and subsidies for electric cars and solar panels (see "Paying for Solar Power," page 88). Above all, he has benefited from a long series of innovations in batteries, solar cells, and space travel. He no more produced the technological landscape in which he operates than the Russians created the harsh winter that allowed them to vanquish Napoleon. Yet in the press and among venture capitalists, the great-man model of Musk persists, with headlines citing, for instance, "His Plan to Change the Way the World Uses Energy" and his own claim of "changing history."

Musk insists on a success story that fails to acknowledge the importance of support from the government.

The problem with such portrayals is not merely that they are inaccurate and unfair to the many contributors to new technologies. By warping the popular understanding of how technologies develop, great-man myths threaten to undermine the structure that is actually necessary for future innovations.

Space cowboy

Elon Musk, the best-selling biography by business writer Ashlee Vance, describes Musk's personal and professional trajectory—and seeks to explain how, exactly, the man's repeated "willingness to tackle impossible things" has "turned him into a deity in Silicon Valley." Born in South Africa in 1971, Musk moved to Canada at age 17; he took a job cleaning the boiler room of a lumber mill and then talked his way into an internship at a bank by cold-calling a top executive. After studying physics and economics in Canada and at the Wharton School of the University of Pennsylvania, he enrolled in a PhD program at Stanford but opted out after a couple of days. Instead, in 1995, he cofounded a company called Zip2, which provided an online map of businesses—"a primitive Google maps meets Yelp," as Vance puts it. Although he was not the most polished coder, Musk worked around the clock and slept "on a beanbag next to his desk." This drive is "what the VCs saw—that he was willing to stake his existence on building out this platform," an early employee told Vance. After Compaq bought Zip2, in 1999, Musk helped found an online financial services company that eventually became PayPal. This was when he "began to hone his trademark style of entering an ultracomplex business and not letting the fact that he knew very little about the industry's nuances bother him," Vance writes.

When eBay bought PayPal for $1.5 billion, in 2002, Musk emerged with the wherewithal to pursue two passions he believed could change the world. He founded SpaceX with the goal of building cheaper rockets that would facilitate research and space travel. Investing over $100 million of his personal fortune, he hired engineers with aeronautics experience, built a factory in Los Angeles, and began to oversee test launches from a remote island between Hawaii and Guam. At the same time, Musk cofounded Tesla Motors to develop battery technology and electric cars. Over the years, he cultivated a media persona that was "part playboy, part space cowboy," Vance writes.

Musk sells himself as a singular mover of mountains and does not like to share credit for his success. At SpaceX, in particular, the engineers "flew into a collective rage every time they caught Musk in the press claiming to have designed the Falcon rocket more or less by himself," Vance writes, referring to one of the company's early models. In fact, Musk depends heavily on people with more technical expertise in rockets and cars, more experience with aeronautics and energy, and perhaps more social grace in managing an organization. Those who survive under Musk tend to be workhorses willing to forgo public acclaim. At SpaceX, there is Gwynne Shotwell, the company president, who manages operations and oversees complex negotiations. At Tesla, there is JB Straubel, the chief technology officer, responsible for major technical advances. Shotwell and Straubel are among "the steady hands that will forever be expected to stay in the shadows," writes Vance. (Martin Eberhard, one of the founders of Tesla and its first CEO, arguably contributed far more to its engineering achievements. He had a bitter feud with Musk and left the company years ago.)

Elon Musk: Tesla, SpaceX, and the Quest for a Fantastic Future
By Ashlee Vance
Ecco, 2015

The Entrepreneurial State: Debunking Public vs. Private Sector Myths
By Mariana Mazzucato
Anthem, 2013

Steve Jobs
By Walter Isaacson
Simon & Schuster, 2011

Musk's companies also rely on government support and good timing, a reality that Musk tries to obscure. When he bristles at NASA's rules or fails to acknowledge SpaceX's interdependence with the agency, he can seem delusional: "SpaceX is surfing on years and years of government-funded technology and public-sector support," as Mariana Mazzucato, an economist at the University of Sussex and author of *The Entrepreneurial State*, points out. In 2008, after three failed tries, SpaceX

launched its first rocket—enough to earn it a $1.6 billion contract from NASA for flights to the International Space Station. Years later, most of the company's work and plans involve flights to the ISS, which itself exists only as the result of public investment. The core technology of space travel depends heavily on NASA-funded work. This is not to negate the company's innovations—in particular, lowering the cost of rocket launches and perhaps fanning visions of space exploration cheap enough for non-billionaires. But SpaceX is not driving the future of space exploration. It is capitalizing on a deep pool of technology and highly trained people that already existed, and it is doing so at a moment when national support for NASA has diminished and the government is privatizing key aspects of space travel.

Likewise, Musk's success at Tesla is undergirded by public-sector investment and political support for clean tech. For starters, Tesla relies on lithium-ion batteries pioneered in the late 1980s with major funding from the Department of Energy and the National Science Foundation. Tesla has benefited significantly from guaranteed loans and state and federal subsidies. In 2010, the company reached a loan agreement with the Department of Energy worth $465 million. (Under this arrangement, Tesla agreed to produce battery packs that other companies could benefit from and promised to manufacture electric cars in the United States.) In addition, Tesla has received $1.29 billion in tax incentives from Nevada, where it is building a "gigafactory" to produce batteries for cars and consumers. It has won an array of other loans and tax credits, plus rebates for its consumers, totaling another $1 billion, according to a recent series by the *Los Angeles Times*.

It is striking, then, that Musk insists on a success story that fails to acknowledge the importance of public-sector support. (He called the *L.A. Times* series "misleading and deceptive," for instance, and told CNBC that "none of the government subsidies are necessary," though he did admit they are "helpful.")

If Musk's unwillingness to look beyond himself sounds familiar, Steve Jobs provides a recent antecedent. Like Musk, who obsessed over Tesla cars' door handles and touch screens and the layout of the SpaceX factory, Jobs brought a fierce intensity to product design, even if he did not envision the key features of the Mac, the iPod, or the iPhone. An accurate version of Apple's story would give more acknowledgment not only to the work of other individuals, from designer Jonathan Ive on down, but also to the specific historical context in which Apple's innovation occurred. "There is not a single key technology behind the iPhone that has not been state funded," says economist Mazzucato. This includes the wireless networks, "the Internet, GPS, a touch-screen display, and … the voice-activated personal assistant Siri." Apple has recombined these technologies impressively. But its achievements rest on many years of public-sector investment. To put it another way, do we really think that if Jobs and Musk had never come along, there would have been no smartphone revolution, no surge of interest in electric vehicles?

We should determine technological priorities without giving excessive weight to the visions of a few tech celebrities.

This matters because the great-man narrative carries costs. First, it has helped to corrode the culture of Silicon Valley. Great-man lore helps excuse (or enable) some truly terrible behavior. Musk is known, after all, for humiliating engineers and firing employees on a whim. In 2014, when his assistant, who had

devoted her life to Tesla and SpaceX for 12 years, asked for a raise, he summarily let her go. Nor can Musk's rough edges be justified as good for business. Rather, they have the potential to jeopardize crucial relationships with government agencies, according to a former official interviewed by Vance: Musk's "biggest enemy will be himself and the way he treats people." Similarly, Jobs was known for entitled behavior and brutishness to employees. Yet as Walter Isaacson has written in his biography, *Steve Jobs*: "Nasty was not necessary. It hindered him more than it helped him." If Silicon Valley, with its well-documented problems with diversity, is to attract a broader pool of talented people, encouraging more supportive managerial practices and telling more inclusive stories about who matters would surely help.

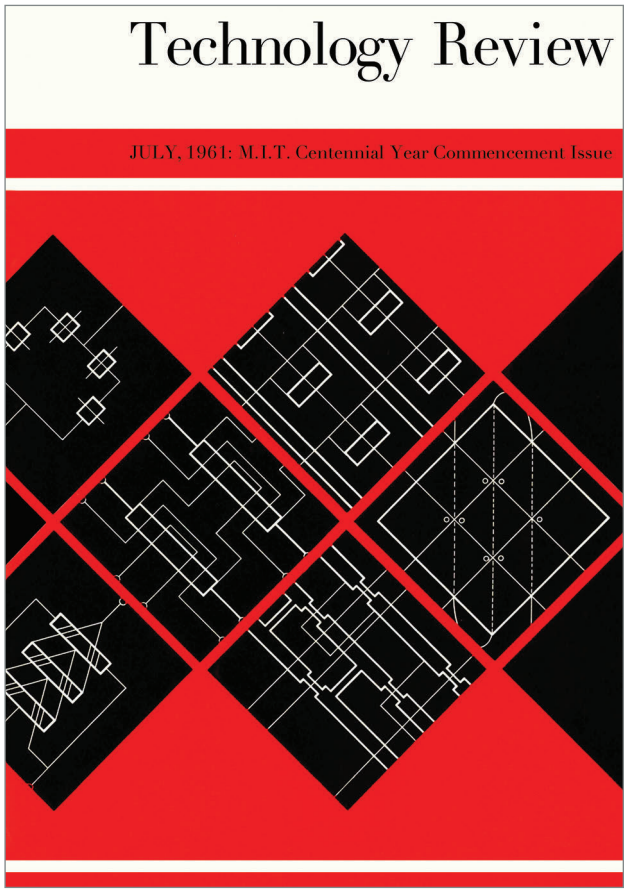
Hero myths like the ones surrounding Musk and Jobs are damaging in other ways, too. If tech leaders are seen primarily as singular, lone achievers, it is easier for them to extract disproportionate wealth. It is also harder to get their companies to accept that they should return some of their profits to agencies like NASA and the National Science Foundation through higher taxes or simply less tax dodging.

And finally, technology hero worship tends to distort our visions of the future. Why should governments do the hard work of fixing and expanding California's mass transit system when Musk says we could zip people across the state at 760 miles per hour in a "hyperloop"? Is trying to colonize Mars, at a cost in the billions of dollars, actually the right direction for future space exploration and scientific research? We should be able to determine long-term technology priorities without giving excessive weight to the particular visions of a few tech celebrities.

Rather than placing tech leaders on a pedestal, we should put their successes in context, acknowledging the role of government not only as a supporter of basic science but as a partner for new ventures. Otherwise, it is all too easy to denigrate public-sector investment, eroding support for government agencies and training programs and ultimately putting future innovation at risk. As Mazzucato puts it, "It's precisely because we admire Musk and think his contributions are important that we need to get real about where his success actually comes from."

Contributing editor Amanda Schaffer has also written for Slate *and the* New Yorker.

54 Years Ago



Books over Bullets

We don't make ourselves safer by favoring military spending over education, a broadcasting executive argued.

"Since the end of World War II, the United States has spent some $85 billion for foreign aid. Of this, $12 billion went into the Marshall Plan, the greatest act of reconstruction in history. Since 1952, the vast bulk of the remaining $73 billion has gone to military, mutual security, technical, and industrial purposes. Only an incidental trickle has borne directly on education—which we ourselves have called the first prerequisite of a democratic society. One by one the emerging nations of Africa and Asia have said that education is their first concern. One by one they have given it the largest share of their limited revenues. And one by one they have seen us neglect to give to their educational development the same high priority we have given their economic and military development.

Military aid can become a powder keg in the hands of a people unless they are educated. I am sure that education is the neglected world frontier. As the world's leading democracy we ought to take a good hard look at our national policy on foreign aid and see if we are doing enough to prepare the emerging nations to be truly self-governing and self-sufficient.

It may be that democracy will be irreparably damaged if the Russians get to the moon before us. I don't know. But of this I am absolutely certain: democracy cannot survive ignorance, superstition, and all the awful uncertainty, the fatal incompetence and the harsh defensiveness of those who have neither knowledge nor understanding—for they will be easy and inevitable victims of aggression from without or corruption from within.

Only education—not manned flights to the moon, not new nuclear tests below the surface or in outer space, not webs of highways and patches of landing fields dotting half the planet—can ultimately prevent the sure collapse of a free nation unequal to its freedom."

Excerpted from an MIT commencement address by Frank Stanton, who was president of CBS from 1946 to 1971. It was published in the July 1961 issue of Technology Review *under the headline "An Educational Marshall Plan."*

MIT Technology Review (ISSN 1099-274X), September/October 2015 Issue, Reg. U.S. Patent Office, is published bimonthly by MIT Technology Review, 1 Main St. Suite 13, Cambridge, MA 02142-1517. Periodicals postage paid at Boston, MA, and additional mailing offices. Postmaster: send address changes to MIT Technology Review, Subscriber Services, PO Box 5001, Big Sandy, TX 75755, or via the Internet at www.technologyreview.com/customerservice. Basic subscription rates: $41.94 per year within the United States; in all other countries, US$54. Publication Mail Agreement Number 40621028. Send undeliverable Canadian copies to PO Box 1051 Fort Erie, ON L2A 6C7. Printed in U.S.A. Audited by the Alliance for Audited Media

ANALOG DEVICES

AHEAD OF WHAT'S POSSIBLE™

ADI IS PROUD TO BE THE FOUNDING MEMBER OF SOLVE

SCIENCE FICTION BECOMES FACT

MEET LUKE, FROM DEKA RESEARCH AND DEVELOPMENT CORP.

It is the most advanced prosthetic arm approved by the FDA that can perform highly complex tasks, like picking up a grape. ADI is proud to deliver trusted, high-performance technology to help make DEKA's revolutionary innovation possible – and improve quality of life for its users.

#ADIahead

SEE HOW DEKA IS TRANSFORMING TECHNOLOGY— AND LIVES

analog.com/AWP/DEKA

We create chemistry that helps lush landscapes love thriving cities.

The construction industry currently accounts for about half of the world's consumption of energy and resources. It's a substantial amount - but it can be reduced, if you just add the right chemistry.

We've developed a number of solutions that make construction more mindful of the environment and buildings that are more durable and efficient throughout their life cycle. The result is that new developments are less taxing on our finite resources in the short and long term.

When we can build more while using less, it's because at BASF, we create chemistry.

To share our vision visit wecreatechemistry.com/construction

150 years

BASF

We create chemistry